GEOTHERMAL EXPLORATION UNDER THE SALTON SEA USING MARINE MAGNETOTELLURICS

FINAL REPORT 2006

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Governor

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
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- Transportation

The Geothermal Exploration under the Salton Sea using Marine Magnetotellurics is the final report for the Schlumberger project, grant number GEO-02-005, conducted by Schlumberger. The information from this project contributes to PIER's Renewable Energy Technologies Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

The Salton Sea Geothermal field, one of the largest resources of this type in the world, lies at the southern shore of the Salton Sea in Imperial County, California. The field has only been developed on the southeastern shore of the Salton Sea; no development has been made offshore mainly because geophysical data is not available. This project was to apply new marine magnetotelluric technology in an integrated approach to delineate potential geothermal reservoirs extending beneath the Salton Sea. Marine magnetotelluric technology is a shallow water-body application of a low-frequency electromagnetic induction method for determining the subsurface distribution of electrical resistivity using measurements of naturally occurring magnetic and electric fields on the surface of the Earth. This technology provides geothermal developers a new technique to better evaluate potential reservoir areas in a marine environment. In turn, this will enable effective exploration in new areas, develop and produce geothermal fields more efficiently, drill fewer dry holes, and reduce the cost of electricity generation.

This project successfully demonstrated the first ever combined land/marine magnetotelluric survey, which delineated the geothermal reservoir extending beneath the Salton Sea and provided valuable structural geophyisical data of the area, especially in a shallow marine environment. Through this technology the unknown geothermal field boundaries and internal structure were mapped to more than 10 kilometers past the known field boundaries. This project consisted of the following tasks:

- Instrumentation modifications and test surveys.
- survey consisting of a combined land-based and a marine phase.
- Data integration and interpretation.

Keywords: Salton Sea geothermal field, magnetotelluric technology, marine magnetotellurics, profile lines, data integration and interpretation

Executive Summary

This project applied marine magnetotelluric (MMT) technology in an integrated approach to chart potential geothermal reservoirs extending beneath the Salton Sea. MMT is a shallow water-body application of a low-frequency electromagnetic induction method for determining the subsurface distribution of electrical resistivity using measurements of naturally occurring magnetic and electric fields on the surface of the Earth. It was anticipated that this technology will provide geothermal developers with a new technique to better evaluate potential reservoir areas in a marine environment. This would enable effective exploration in new areas and develop and produce geothermal fields more efficiently, by drilling fewer dry holes and reducing the cost of electricity generation.

The Public Interest Energy Research (PIER) Program's goals for this project were to lower the risks and associated costs of developing a geothermal resource by improving exploration methods, improve understanding of basic geological conditions associated with hydrothermal systems, and enhance reservoir management. The overall economic goal of this project was to develop and test a commercially viable exploration and monitoring technology for the geothermal industry.

The project demonstrated the first combined land/marine magnetotelluric (MT) survey, which charted the geothermal reservoir extending beneath the Salton Sea. In addition, it provided valuable structural geophyisical data of the area, especially in a shallow marine environment. The unknown geothermal field boundaries and internal structure were mapped to more than 10 kilometers past the known field boundaries. The project results were announced at the 2006 Geothermal Resources Council Annual meeting in San Diego.

Project consisted of the following tasks:

- instrumentation modifications and test surveys,
- MT survey consisting of a combined land-based and a marine phase; and,
- data integration and interpretation.

The first task included modifying extensively the MT instruments, and conducting three test surveys to test the functionality of the MT instruments, measuring initial field resistivities, and identifying potential stations for the combined land and marine phases. The instruments were redesigned, programmed, and fabricated. The instruments were deployed in shallow water transition zones and operated on a flat raft-like structure that would secure and protect the instruments for the length of the recording periods. Marine- and land-based instruments were deployed during the test surveys to identify stations, set data acquisition parameters, specify noise levels, record times, processing schemes and development of techniques to reduce electrical noise originating from the geothermal power plants and mechanical noise from wave activity in the sea.

The second task consisted of a full-scale MT survey that included both land-based and marine phases. The survey was conducted over the known portion of the geothermal field and the unknown surrounding region to determine its formation geological resistivity signature. The survey was used to map the unknown geothermal field boundaries and internal structure.

The third task consisted of data integration and its interpretation with the existing field model. The results obtained by the MT survey were consistent with previous surveys and well drilling information. The results suggest that significant geothermal resource extends offshore and future efforts should be directed toward recovery of this geothermal resource.

California has long been a leader in technology development; it is the nation's capitol for new ideas, now there is another one. This new technology is useful for geothermal field development within and outside the state. The technology is also has petroleum and environmental applications, which have a continued and growing presence in California.

To interpret the data from this research, hardware and software is being developed by a California based technology center for continued commercial use. This process provides a number of good quality high-technology jobs to the state.

1 Introduction

1.1 Background and Overview

The Salton Sea Geothermal Field lies at the southern shore of the Salton Sea in the Imperial County of Southern California. The field, one of the largest resources of the hydrothermal type in the world, was first discovered in the 1950s but has thus far only been developed on the southeastern lakeshore, although perhaps the bulk of the resource lies offshore (Hulen et al., 2003)[1]. The actual field boundaries are still not well known. The field has only been developed on the southeastern shore of the Salton Sea; no development has been made offshore mainly because geophysical data is not available.

The purpose of this project was to apply new marine magnetotelluric (MMT) technology in an integrated approach to delineate potential geothermal reservoirs extending beneath the Salton Sea. It is anticipated that this technology will provide geothermal developers with a new technique to better evaluate potential reservoir areas in a marine environment. This will enable effective exploration in new areas and develop and produce geothermal fields more efficiently, drill fewer dry holes and reduce the cost of electricity generation.

Magnetotellurics (MT) is a natural-source, electromagnetic geophysical method of imaging structures below the earth's surface. Natural variations in the earth's magnetic field induce electric currents under the earth's surface. Electrical conductivity of rocks and sediments display a wide range of electrical conductivities. The earth's naturally varying electric and magnetic fields are measured over a wide range of frequencies. These fields are due to electric currents (telluric currents) that flow in the Earth and the magnetic fields that induce these currents. The magnetic fields are produced mainly by the interaction between the solar wind, the ionosphere and distant thunderstorm activity. The ratio of the electric field to magnetic field can give simple information about the subsurface conductivity. Because of the skin effect phenomenon that affects electromagnetic fields, the ratio at higher frequency ranges gives information on the shallow earth, whereas deeper information is provided by the low-frequency range. The ratio is usually represented as MT apparent resistivity and phase as a function of frequency. Imaging of the Earth's subsurface conductivity is an important in identifying rock formations, understanding tectonic processes, and geologic structures. MT measures these natural fields over a range of frequencies and uses computer based models to convert these data into a model of resistivity versus depth. MT is a standard exploration method that has been widely used for more than 50 years in geothermal, oil, mineral, groundwater exploration and monitoring. With MT it is possible to gain insight into the resistivity structure of the surrounding material from surface to great depths.

One of the goals for this project was to lower the risks and associated costs of developing a geothermal resource. This would be accomplished by improving exploration methods, improving understanding of basic geological conditions associated with hydrothermal systems, and enhancing reservoir management. This project demonstrated the capability of a

MT survey to delineate the boundaries and characteristics of the geothermal reservoir by interpreting the markedly different resistivity signature from the background formation. The project demonstrated that the electrical information obtained is important for understanding the geothermal reservoir. The results obtained by the MT survey were consistent with previous surveys and well drilling information.

This project highlighted the capability of a shallow water MMT technique that has better defined the characteristics and extent of the geothermal reservoir on land and underneath the Salton Sea along the four profile lines with the exception where data collection was hampered by uneven data quality and low resolution along the Line 1_ 1kmE, profile line several miles off-shore. The survey was conducted over the known portion of the geothermal field and the unknown surrounding region to determine its formation resistivity signature. The survey was used to map the unknown external geothermal field boundaries and internal structure.

This project consisted of the following tasks: 1) instrumentation modifications and test surveys, 2) MT survey consisting of a combined land-based and a marine phase; and, 3) data integration and interpretation.

The first task was composed of extensive MT instrumentation modifications and conducting three test surveys to test the functionality of the instruments, measure initial field resistivities and identify potential stations for the combined land and marine phases. The instruments required significant engineering and programming modifications for either land-based or shallow water applications. Instrument modifications included redesign, fabrication and adapting the marine instruments to operate on a flat raft-like structure that would secure and protect the marine instruments for the length of the recording periods in shallow water transition zones. Marine and land-based instruments were deployed during the test surveys to identify stations, set data acquisition parameters, specify noise levels, recording times, processing schemes and development of techniques to mitigate electrical noise originating from the geothermal plant and mechanical noise from wave activity in the sea.

The second task consisted of a full-scale MT survey that included both land-based and marine phases. The survey was conducted over the known portion of the geothermal field and the unknown surrounding region to determine its formation resistivity signature. The survey was used to map the unknown external geothermal field boundaries and internal structure. The survey was conducted along four profile lines. Three of the four profile lines were strategically placed to cross the northeast trending geothermal field in a northwest-southeast direction. The fourth profile measured directly across the field in a north direction to establish the lateral boundaries and also to map the basin structure. The survey was conducted with land, marine and hybrid field instruments. The instruments used a portable, low-power digital data acquisition system with sensors deployed on land, within the Salton Sea and in the shallow-water transition zones. For the land-based phase, the instruments were deployed for a three-week period. Six to eight stations were installed and monitored for a period of one to two days. It was possible to re-deploy instruments if local conditions were too noisy or the instruments failed. For the marine phase, the instruments were initially deployed to test specific noise levels and recording times and to develop techniques to mitigate electrical noise originating from the geothermal plant and mechanical noise from water wave activity. The deployment of the instruments required special marine conveyance rafts with a shallow-bottom and a large deck, in water deeper than 10 feet. These systems were then redeployed to another site until all stations were covered. It was possible to redeploy noisy stations several times if local conditions were noisy, or if the instrumentation failed because the data quality could be evaluated on site.

The third and most important task of the project was data integration and its interpretation with the existing field model. A preliminary model based primarily on the MT results is provided; however, it is expected that this model will be updated as these data are combined with existing and future geophysical and well data. It was expected that the high temperature and high salinity of the formation brines would produce an anomalously low resistivity that would allow differentiation of the geothermal resource from the surrounding formation. The results obtained by the MT survey were consistent with previous surveys and well drilling information.

MTs has long been a geothermal industry method to assess great depths of penetration but there were occasions in the conduction of the survey where this methodology was hampered by uneven data quality and low resolution. These events occurred at stations where noise levels due to wave action or power plant interference occurred. However, for this project more than seventy land and marine soundings were conducted in three separate measurement trials. Data quality was excellent and the coverage was exceptional. Fully 50 percent of the stations were recorded near or offshore and coverage was extended to more than ten kilometers (km) past the known field boundaries. Not surprisingly, the only noisy stations were located adjacent to the existing power plants and at some marine sites that were occupied during periods of high winds. Data were interpreted with a two-dimensional (2D) inversion code, which provided a resistivity versus depth model across the geothermal field in four profiles lines. The code works by matching model-generated data to field results and adjusting the model until the field and numerical data match within a given tolerance.

The data collected from the measurement trails were processed to provide apparent resistivity and phase as a function of frequency for each survey site. The sites were then grouped into profiles where a 2D inversion code was applied to provide a resistivity versus depth section along the four profile lines. The resistivity versus depth models are more easily computed as 2D profiles; however, with advances in computing power, limited three-dimensional (3D) numerical modeling may now be applied. The field was identified by having considerably lower geothermal resistivity than the background. This was largely due to the higher temperatures and higher formation water salinity within the field. Based on the low resistivity signature it was estimated that the geothermal field encompasses more than 200 kilometer-square (km^2), of which more than half lies offshore. Within the field the profile lines in general matched the known geology and borehole induction resistivity logs very well. The general stratigraphic section can be divided into three vertical horizons, a shallow clay and mud cap rock, an upper reservoir zone consisting of high temperature sand and clays and a deeper more continuous reservoir zone of slightly higher resistivity.

Comparison of the borehole resistivity log to the MT resistivity section indicated that the section could be divided into three or four layers. The upper several hundred meters is a laterally discontinuous low resistivity later associated with a thick low-permeability basin filling clay and local sands. This layer of filling clay and local sands is locally hot and the high temperature could be correlated to the lowest resistivity. Resistivities as low as 0.2 ohm-meter are associated with shallow hot clays overlying the existing geothermal field. The resistivity log also indicated that this layer abruptly terminates into a higher resistivity horizon that correlated with the upper sands of the geothermal field. The resistivity was slightly higher due to porosity reduction by mineral deposition from circulating hot brines. Below the upper sands horizon the resistivity gradually increased due to porosity reduction.

The four profile lines indicated that the upper hundred meter horizon was lowest in resistivity and thickest within the known field although the low resistivity anomaly significantly extends offshore. The deeper layers also had a lower resistivity within the known field and gradually increased in resistivity beneath the sea. Examination of the 2D profiles showed that while most of the known reserves correlate with these local low resistivity zones, some of the anomaly extended offshore to beneath unexplored terrain.

This project has been useful in three areas. First, this was the first combined land/marine MT survey ever conducted and as such, provided valuable engineering data, especially in shallow water. Second, it was the first project to attempt to map a large and important geothermal resource in a shallow marine environment. The results suggest that significant resource extends offshore and future efforts should be directed toward development.

1.1.1 Geologic Setting of the Salton Sea Geothermal System

The Salton Sea geothermal field is located in the Salton Trough (Figure 1). It is the northern landward extension of the Gulf of California tectonic regime, within which oceanic crust is being formed at pull-aparts, or spreading centers, developed at the oversteps between major, en echelon, right-lateral strike-slip faults On land as in the Gulf, these spreading centers are the sites of intense magmatism, volcanism, and high temperature hydrothermal activity. The Salton Sea geothermal system (Figures 1 and 2) is developed above the northernmost of the spreading centers, where interaction between the North American and Pacific plates changes from stretching and crustal extension to dominantly right-lateral slip along the San Andreas transform fault zone (See Figure 1).

Whereas the Gulf of California is a narrow new sea developed above fresh oceanic crust, its extension, the Salton trough, is filled by up to 6 km of Pliocene to Holocene deltaic fluviolacustrine clastic sediments supplied by the ancestral and modern Colorado River. These sediments serve as efficient thermal insulators above the continental spreading centers, enabling the formation of large, hot (up to at least 370°C) hydrothermal systems like those at the Salton Sea and, to the south, Mexico's Cerro Prieto geothermal field. There are few volcanoes exposed in the Salton trough, and all are quaternary. The obsidian butte, at the Salton Sea field (Figure 2) yielded a K-Ar age of 16 ka + 16 ky (Muffler and White, 1969)[2]. Measured temperatures reach 360 Celsius (°C) at total well depth, and range between 323°C and 333°C through the rhyolitic interval. Like all Salton Sea wells, Smith IW-2 is dominated by late Cenozoic, fluviolacustrine sandstones, siltstones, mudstones and probably marls. The Trough first began to form about 4 million years ago (Herzig and Jacobs, 1994)[3], the clastic source for these deposits has been the heavily sediment laden Colorado River (Figure 1).

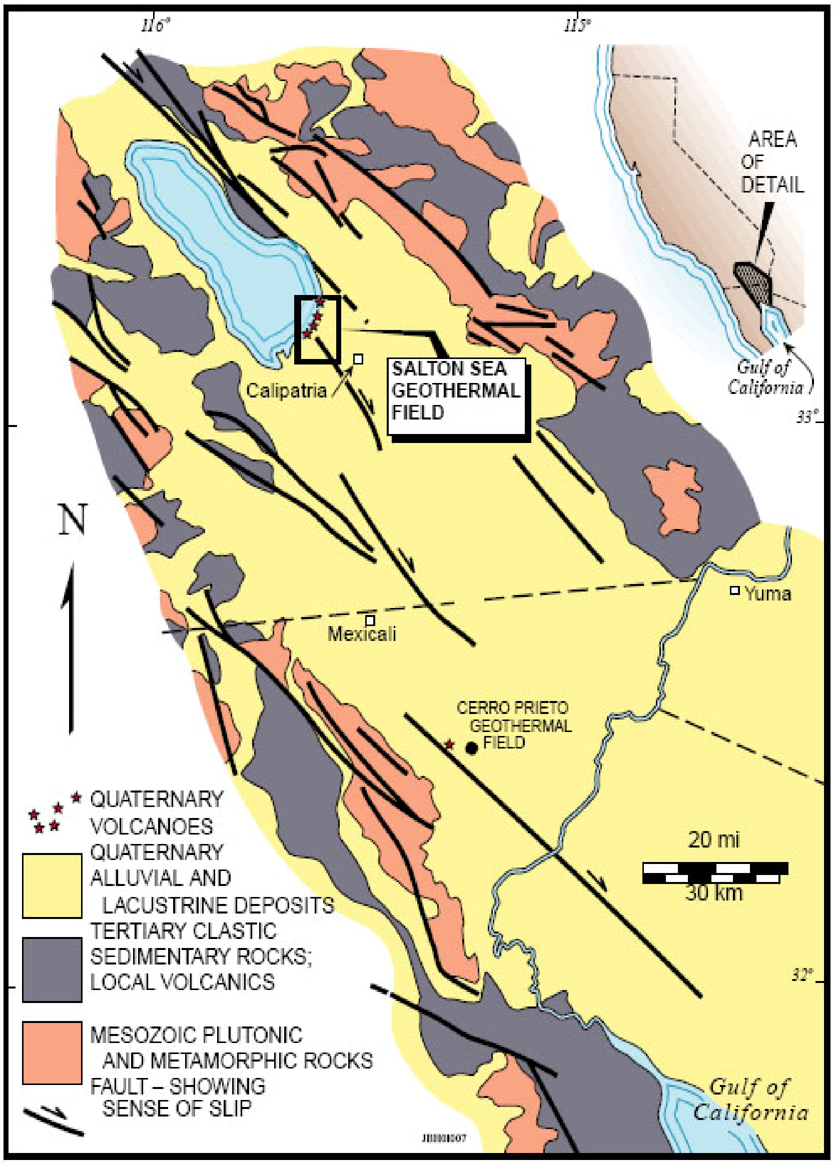

Figure 1: Location and generalized geologic map of the Salton Sea Trough.
(Schlumberger)

Mudstones dominate the upper 400 m of Smith IW-2, and help provide an effective caprock, or top seal, on the underlying, liquid-dominated hydrothermal system (Moore and Adams, 1988[4]; and Elders and Sass, 1988[5]). Below the caprock, the proportion of mudstone to siltstone plus sandstone, averaged over 30-m intervals, is relatively constant at about one to one ratio (1:1). The siltstones and sandstones have a fairly high porosity and good permeability enabling them to be an excellent thick geothermal reservoir. It has been reported that the reservoir permeability is roughly half from the matrix permeability and half from fractures and fault zones. This thick reservoir high porosity, salinity and high temperature provides an excellent electrical target for the MT survey by yielding contrasts of up to 30 times from background cold, and non altered surrounding rocks.

Carbonates, volcanic, and salt all have large electrical resistivity contrasts with typical sedimentary rocks. These rocks are natural applications for MT and are classically difficult sites for seismic methods either because the high reflectivity at the interface with the sediments prevents the recovery of signals beneath such bodies or because internal reflectors effectively shield deeper reflectors. In addition, in the presence of large-scale inhomogeneities, the selection of appropriate migration velocities is essential for the correct 3D placement of interfaces and structure. MT has been used to correct migration velocities yielding significant changes in the images of subsurface structure (Zerilli, 2003[6]). Empirical, site-specific relationships between resistivity and velocity can be developed which then allow the resistivity section to guide the selection and placement of velocities. MT theory is described in greater detail in Appendix F.

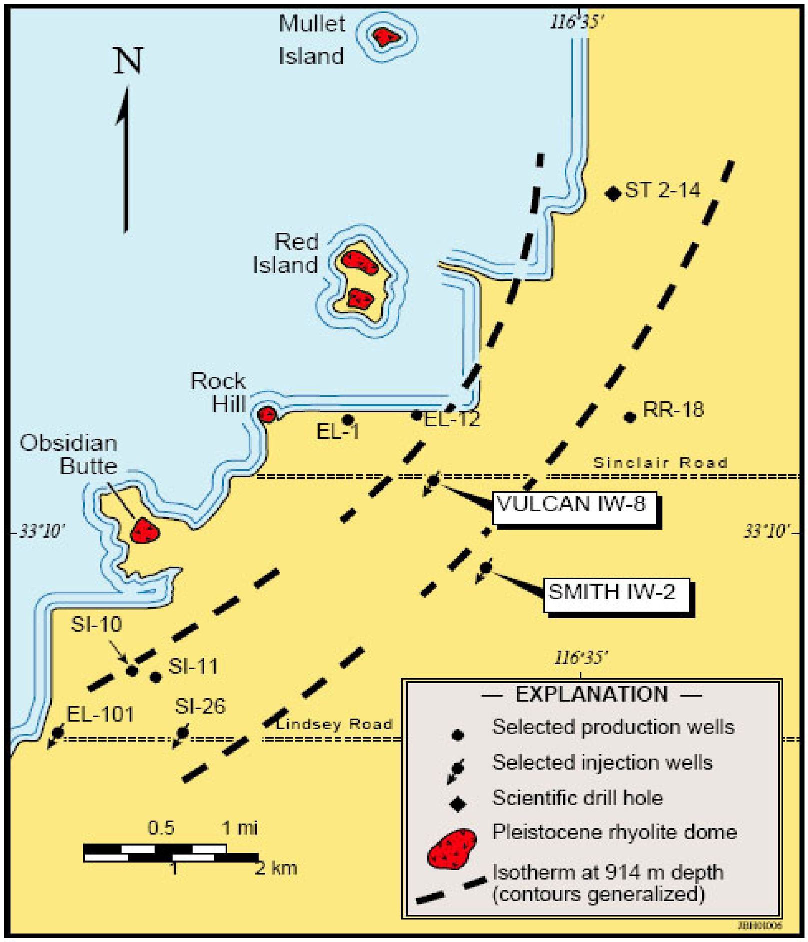

Figure 2: Map of the Salton Sea geothermal field (Schlumberger)

1.1.2 Background of Magnetotelluric Technology (MT)

MT is a low frequency electromagnetic induction method for determining the subsurface distribution of electrical resistivity using measurements of naturally occurring magnetic and electric fields on the surface of the earth. The technology has been under active development since the 1950's. In the last few years, advances in instrumentation, processing and interpretation have increased the method's use in petroleum exploration.

There is a growing recognition of the potential role for MT in exploration programs. However, its market size is less than 1 percent of the seismic method. The advances in interpretation algorithms and instrumentation have been developed separately in universities, government labs and in a few scattered research and development companies.

MT is the ideal complement to, and in some cases replacement for, seismic methods in areas where seismic methods are difficult to implement inexpensively. MT works best in geologic situations where rocks of greatly different electrical resistivity are juxtaposed.

1.2 Project Objectives

The purpose of this development project was to apply new MMT technology in an integrated approach to delineate potential geothermal reservoirs extending beneath the Salton Sea. Schlumberger anticipated that it would provide geothermal developers with a new technique to better evaluate potential reservoir areas in a marine environment. This would enable effective exploration in new areas and develop and produce geothermal fields more efficiently, drill fewer dry holes, and reduce the cost of electricity generation.

The project objectives were:

1. Plan and carry out a MMT survey to determine the location of the boundaries of the Salton Sea Reservoir where it extends under the Salton Sea.
2. Demonstrate how MMT surveys can be extended to water covered areas for geothermal exploration.
3. Provide to the geothermal industry integrated results from the land/ MMT surveys, shallow geothermal gradient surveys, gravity and magnetic surveys, along with the general production knowledge from the reservoir manager.
4. Establish a cost structure for providing commercial MMT surveys to the geothermal industry.

The overall economic goal of this project was to develop and test a commercially viable exploration and monitoring technology for the geothermal industry.

1.3 Report Organization

This report describes a combined offshore/onshore MT survey made over the known geothermal field and surrounding region to determine the formation resistivity signature of the geothermal field and use this to map the external field boundaries and internal structure.

The report is organized into four main sections and six appendices. The body of the report covers survey design and testing, field and marine surveys and data processing and interpretation. The appendices include a detailed summary of the budgets, a list of the site owners, a sample of the letter sent to the landowners for permission to conduct surveys, electronic schematic diagrams and theory of the MT method.

2 Project Approach or Method

A work plan for the project was prepared to identify the tasks, estimate the amount of effort and time for each task.

2.1 Permitting

Schlumberger contacted State and Federal authorities prior to conducting any survey. Schlumberger verified with the California Regional Water Quality Control Board that the MT survey was exempt from California Environmental Quality Act (CEQA) regulations.

The work plan and survey map were discussed with Federal and State and Imperial County representatives on March 12, 2003 at the Sonny Bono Salton Sea National Wildlife Refuge (NWR) at Calipatria, California. The representatives discussed and reviewed the survey plan; addressed concerns about endangered species habitat and road access, and ensured CEQA exemption for the survey. Schlumberger also contacted Imperial County public works representatives and Imperial Irrigation District to advise them of the survey and obtain any needed permits.

After consultation with State and Federal Fish and Wildlife personnel, several sites that were located in potential habitat for endangered Yuma Clapper Rail, or Brown Pelican sites were eliminated. All land sites were located to avoid disturbing any areas on Imperial County roads right of way, or right of way associated with drains and canals. A special use permit was obtained for the survey portion conducted on the NWR. All survey activity on the NWR was carried out in accordance with any and all requirements included in the special use permit.

Schlumberger obtained a senior management letter of support for the project and had it accepted by the California Energy Commission (Energy Commission) to fulfill a special condition requirement of this Energy Commission project. Schlumberger received excellent support from Vince Signorotti of CalEnergy, Robert Worl and Pablo Gutiérrez S. of the Energy Commission in identifying the land owners. Pablo Gutiérrez S. was also the Project Manager of this project. A package containing a cover letter and an authorization form as well as a site map and the project work statement was sent to each owner to request authorization for Schlumberger to temporarily install MT equipment for the survey phases. A list of the site owners and a sample of the cover letter is included in the Appendix.

2.2 Targeting

The initial proposal for the Salton Sea survey was to acquire 70 MT sites. The profile lines were laid out to investigate subsurface electrical structure related to the thermal gradient "pork chop" anomaly shown in Figure 3, from J. Hulen et al, 2003[7] and J. Hulen et al, 2001[8]. Schlumberger planned and permitted for 93 sites (~50 marine and 40 land) with the locations as in Figure 4.

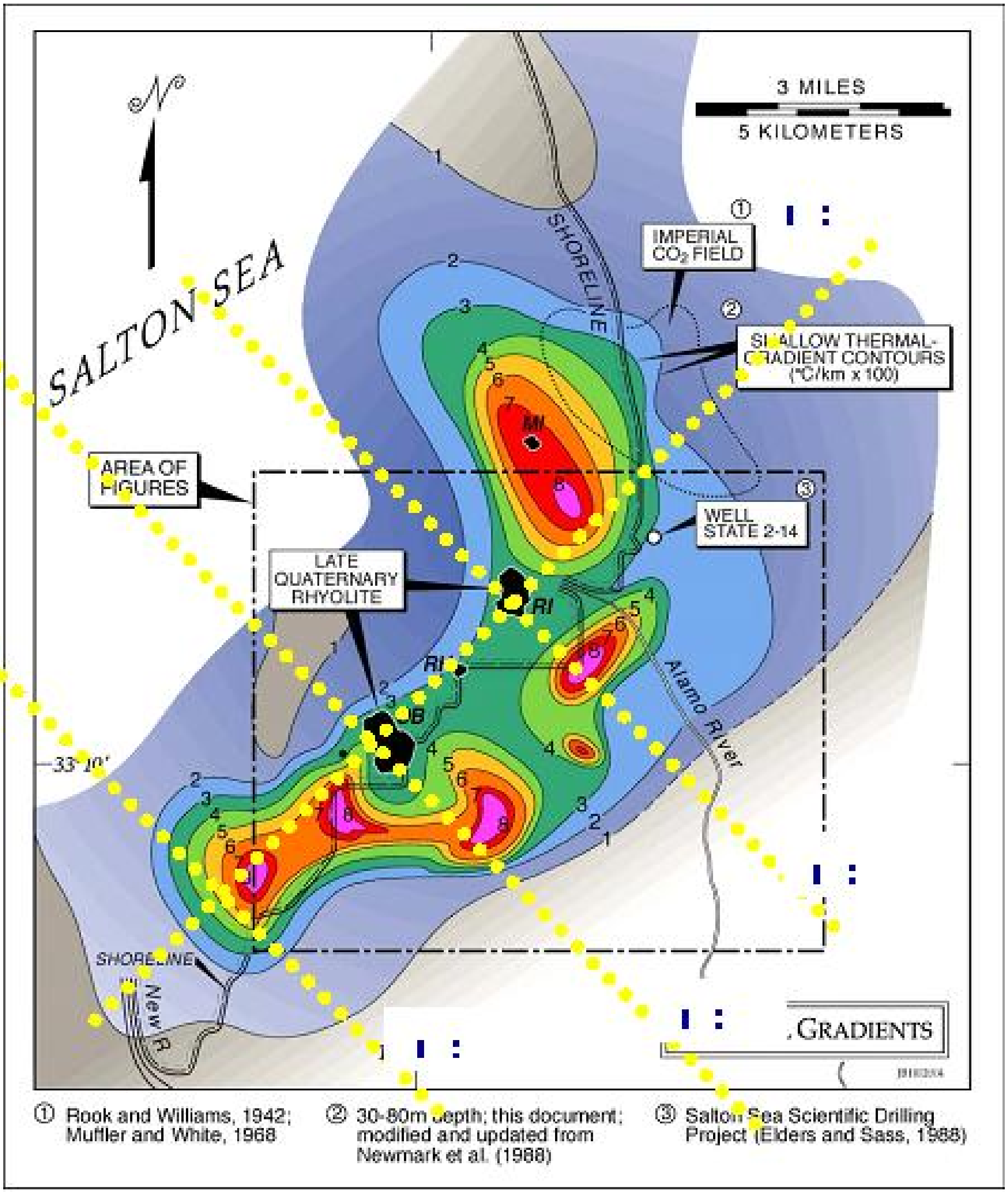

Figure 3: Geothermal gradient pork chop anomaly from J. Hulen et al, 2001, showing location of profile lines. **(Schlumberger)**

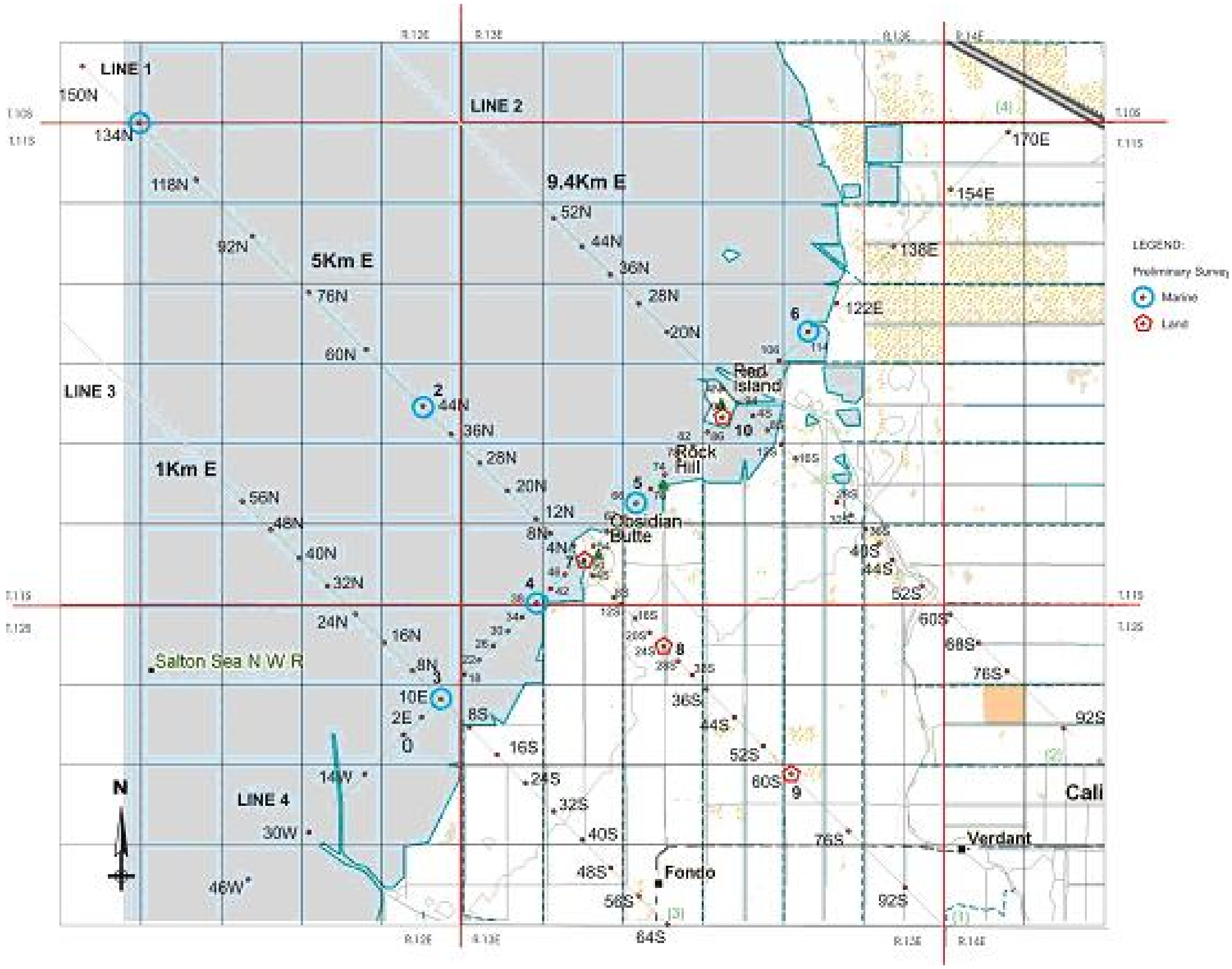

Figure 4: Map of proposed survey sites along 4 profile lines: Line 1_ 1kmE, Line 2_ 5kmE, Line 3_ 9.4kmE and line 4_ Baseline. Total line length was 72 km with 93 sites proposed and more than 30 different land owners. **(Schlumberger)**

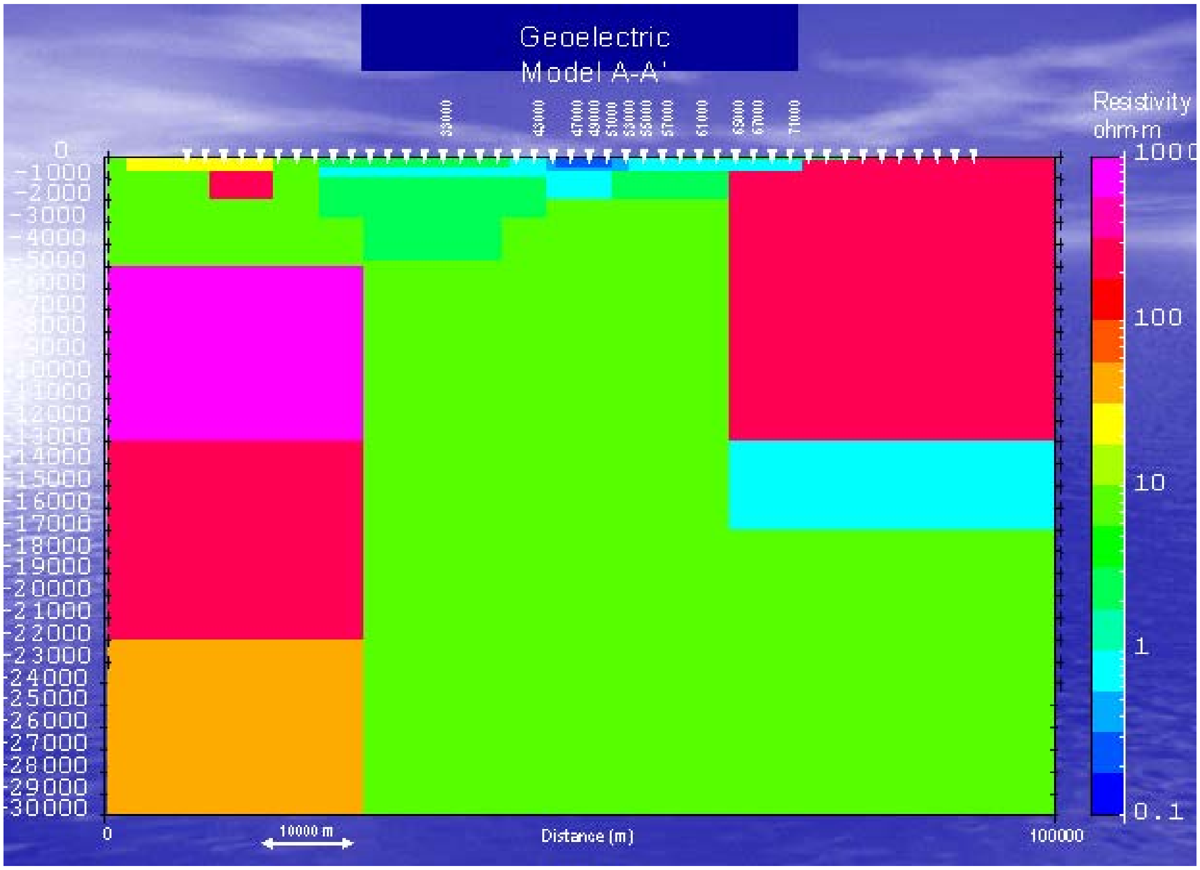

Figure 5: Two-dimensional numerical model of the Salton Sea Basin's electrical structure. (Schlumberger)

A two-dimensional numerical model of the electrical structure of the basin was built using the features identified by Jensen, G., Jiracek, G., and Johnson, Martinez, M. and Romo, J, 1990 [9]. MT parameters calculated at various positions along the section showed that the survey would have sensitivity to the subsurface variations provided there was good quality MT data. The model used for the simulation is shown in Figure 5.

3 Project Outcomes, or Results

Application of MMT technique to geothermal exploration is a new and rewarding technology. Many difficulties and challenges were overcome in the course of the project. Many achievements were made on hardware side, data acquisition, and data processing and interpretation.

Acquiring high-quality MMT data was not an easy task at the Salton Sea. The culture noise due to the geothermal production plants was severe. It was necessary to apply remote reference techniques to suppress the noise in the raw data, and obtain high quality MT data at the local sites. In addition, the storms and wave motions at the Salton Sea made data acquisition difficult. Because of this, some MT data from the marine sites was lost, but on the whole, the data collected was highly satisfactory

Because of the uncertainty in the orientation of the MMT sites, close attention was paid to impedance rotation. This required finding a 'principal direction' at each marine site, and then rotating the impedance along this direction to obtain Transverse Electric/Transverse Magnetic (TE/TM) mode data. This contrasted to the procedure for land sites where all the impedance data was rotated to an estimated strike direction.

Advanced MT inversion technology was applied to extracting electrical resistivity information from the acquired data. Four resistivity profiles were obtained, which appeared consistent, and a good general match to the geologic structure of the area. The more detailed features in the inverted profiles may be useful to further geothermal exploration and production.

3.1 Test Survey

Test surveys were conducted to evaluate the noise conditions and verify the acquisition of acceptable data in the land and marine environments. There were concerns about the level of electromagnetic noise since there were several large geothermal facilities that had been installed after the early surveys of the 1980's. One week of survey time was budgeted for this phase of the survey. Schlumberger extended the testing stage to include three separate field trips. This extra work was needed to test improvements in the equipment and verify feasibility of the marine survey. The three test surveys were conducted in September 2003 (Test Survey A), December 2003 (Test Survey B) and March 2004 (Test Survey C).

Test Survey A - A total of nine MT sites were deployed in three days, starting September 23rd. Data acquisition continued for five days until the marine and land based systems were recovered on the 29th of September. The survey crew was comprised of three Schlumberger personnel, one independent consultant, two local helpers and one Department of Fish and Game (DFG) operator. Unfortunately, the units were not Global Positioning System **(**GPS) synchronized due to a faulty cable that was not detected during the survey. It was concluded that remote reference processing was necessary for the later survey phase.

Test Survey B - This was a two-week land survey and included the search and setup of a remote reference site to aid in processing the land data.

Test Survey C - This was a two-week test experiment consisted of one land site and several marine sites. Two new remote reference sites were occupied to aid in the remote reference processing.

3.2 Field Survey

3.2.1 Marine System Electronics Overview

The Marine Magnetotelluric 24-Bit (MMT24) is the first fully integrated commercial system incorporating the new technology. Figure 6 gives a block diagram of the acquisition electronics. The MMT24 system featured:

- Dual 24 bit Analog to Digital (A/D) converters per channel - one for continuous low frequency data acquisition and one for high frequency acquisition
- High accuracy timing reference (Typical stability > 100 ppb over temperature)
- GPS synchronization and time drift measurement capability
- Compact Flash Data Storage
- High speed port for data storage
- External removable battery pack
- Electronic orientation measurement (three component accelerometer and magnetometers)
- Power status measurements – current and voltage

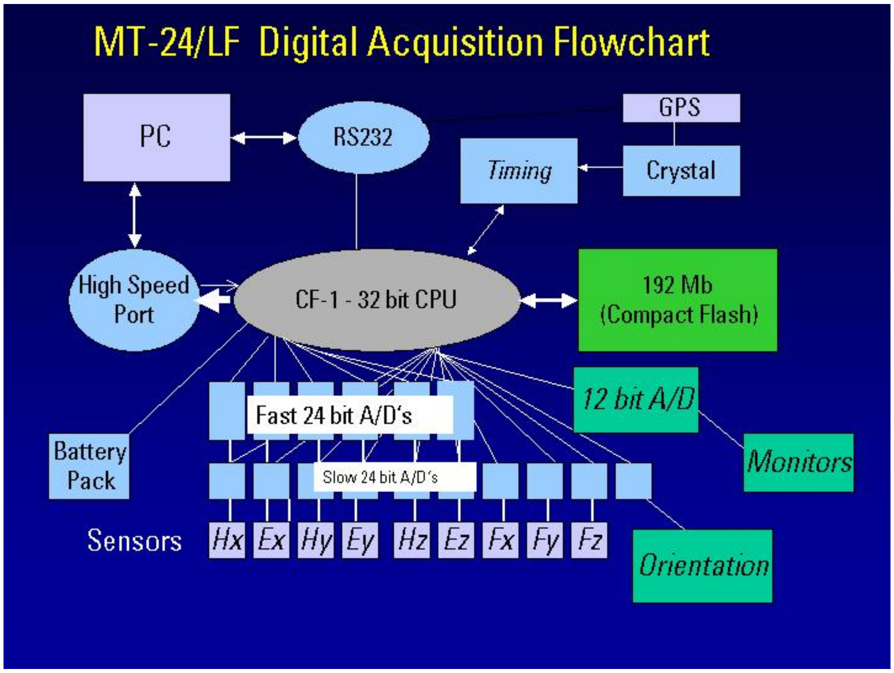

Figure 6: Schematic of MMT24 electronics **(Schlumberger)**

The feature of having dual A/D converters allowed the system to continuously record data at 6.25 Hertz (Hz) for all the time the system was deployed with short synchronized high frequency bands sampled at 50 or 500 Hz. This design saved data storage space and power consumption by shutting off the high frequency after sufficient data had been collected for the higher frequency measurements.

Processing of marine MT data proceeded as with land MT data, the goal of the processing was to provide the best spectral estimates of the MT parameters at each survey site. The processing steps were:

1. Collection of time series for each site
2. Orientation correction for each site
3. Creation of combined data files
4. Calculation of Cross spectral matrix (crosspowers)
5. Estimation of MT spectral functions.

3.2.1.1 Collection of Time Series for Each Site

Each MMT24 system had its own independent data acquisition which recorded the continuous time series onto compact Flash disks inside each MMT24 system. The systems were GPS time-synchronized on deck prior to deployment. Each system then acquired data continuously with timing derived from internal reference. For the Salton Sea survey, all systems collected data at 6.25 Hz.

The first step in processing consisted of recovering the data from the systems and visually inspecting the time series to evaluate data condition.

The acquired data was stored in Compact Flash (CF) as a set of compressed binary files. The data was extracted either directly from CF by using either a CF reader connected to the PC, or a cable connected between the PC parallel port and the MMT24. The extraction program decompressed the time series on the PC in the MT-24 format using ACQ24 and MTR95 processing codes. Processing began with examining the time series visually on the computer screen to check for obvious noise and instrument problems.

Marine electromagnetic data was subject to signals and noises from many sources; hence considerable attention was needed to all aspects of the measurement. One of the most troublesome noises was from motion of the measurement platform. This was generally seen as sinusoidal oscillations of the magnetic field data with little or no associated signals on the electric fields. The magnetic fields were extremely sensitive to motion since the sensor noise level was less than .001nanoTesla (nT) whereas the earth's DC field was ~50,000 nT. Thus rotation of the measurement direction by 1 microradian would correspond to a change 50 times larger than this (.05 nT). The exquisite stability required for accurate measurements, required the instrument package to have a large anchor, be settled firmly on the bottom and present the currents with as small a surface area as possible. Fluctuations of marine currents would sway or rock the sensors. Additionally, the movement of a conductive fluid in the presence of the earth's magnetic field also created an electromagnetic field. (In fact the measurement of electric potentials in the ocean is a standard method to determine water velocity). Thus current variations, eddies and solution waves would generate additional fields. One advantage of marine measurements was that the environment was stable in temperature, generally very close to four degrees Celsius. During the recordings, it was not unusual to have various sharp signals, probably caused by some kind of marine life bumping the sensors or swimming past. The large volume of conductive fluid made a good shield to keep out unwanted high frequency electromagnetic signals. The high pressure salt water environment was also a challenge in ensuring that all connections remained watertight and corrosion free. Because of the extremely low noise signals, corrosion signals could be very troublesome. These challenges applied not only to the electrical connections, but to any exposed metallic parts since these could set up significant corrosion currents.

The MT survey exhibited many of these kinds of interference. Most of the magnetic sensors on all the deployed MMT24 systems demonstrated various kinds of oscillations caused by movement of the structure. Typically this signal seemed to have a strong frequency around 0.2 Hz related to surface wave levels.

3.2.1.2 Orientation Correction

There was no control of the system orientation during deployment, other than the anchor and flotation to ensure that the base was down. Orientation information was electronically recovered from an internal three-axis magnetoresistive element and a three-axis accelerometer. These sensors were digitized and recorded to a log file every six hours. The tilt of the system was determined from the accelerometer measurements. The sensor measurement directions were determined from the magnetoresistive measurements by solving for the direction of the Earth's DC field and knowledge of the magnetic declination at the site. Once the bottom orientation was determined, the MT measurements were rotated into desired survey directions using a standard trigonometric rotation matrix applied to the electric and magnetic fields.

$$\begin{bmatrix} Ex^r(t) \\ Ey^r(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} Ex(t) \\ Ey(t) \end{bmatrix}$$

Equation 1[10]

These calculations were performed inside ACQ24 and new rotated time series were calculated. The marine sites were rotated to ensure the impedance polar diagrams at 0.01 Hz frequency was in alignment with the land sites. These rotated time series are used for the remaining processing.

3.2.1.3 Combined Data Files

Time alignment of the different sites time series data was done using the time shift function inside ACQ24 program. All of the 6.25 Hz acquisition was started on deck just before system deployment. Absolute time was maintained using the internal high accuracy oscillator contained within each MMT24 system. The start of each time series was deleted to maintain a common set of overlapping data for further processing.

3.2.1.4 Calculation of Cross Spectral Matrix

The goal of MT data processing was to accurately define the frequency dependence of MT parameters. The time series data was converted from time series to the frequency domain through a Fourier analysis, typically a Fast Fourier Transform (FFT)[11]. This analysis was carried out using ACQ24 for non-overlapping contiguous segments of 1024 points. Each segment had the mean and linear trend removed and was tapered using a cosine window prior to FFT calculation using standard C routines developed inside ACQ24 by Nestor Cuevas (Schlumberger).

From the Fourier estimates short overlapping segments of 256 points of the input time series were used to get Fourier coefficients for the highest possible frequencies. The time series, originally sampled at a rate of 6.25 Hz, were then digitally low pass filtered and decimated by a factor of four and new Fourier coefficients were calculated. This process was repeated several times, decimating to ever lower sampling frequencies. For this survey the data were decimated to level 5, an effective sampling frequency of 0.006 Hz.

Once in the frequency domain, the calibration parameters at each frequency for each type of channel convert the electric field into mv/km and magnetics into nT. These calibrations included response corrections for the MMT24 acquisition system, such as channel gain, filter response, dipole length and A/D conversion factors.

Next the corrected Fourier coefficients were either simply combined or robust schemes such as the multi-station robust remote reference approach originally described by Egbert, G. D., 1997[12] were applied to calculate the cross spectral matrix.

3.2.1.5 MT Parameter Calculation

Conventional MT processing using a single reference site was applied using either simple coherency sorting or robust down-weighting of the outliers such those as implemented by Egbert, G.D.[12], Jones et al[13,] or Thomson et al[14] could be applied. For this data Schlumberger found a relatively simple selection of the best 15 cross power estimates (highest coherency Hx-Ey, Hy-Ex) gave fairly reasonable MT estimates.

Schlumberger also used the MT workstation processing package LMMT_XP developed by Andrea Zerilli (Schlumberger) to compute the cross spectral matrix from which the impedance tensor was determined. As a final step the data were put into "RES2" format, developed by Electromagnetic Instruments, which was used as input into the Geophysical Earth Model (GEM) modeling package developed by Mike Hoversten, Lawrence Berkeley National Laboratory (LBNL)[15].

The MT estimates for the sites were presented in the attached Electronic Data Interchange (EDI) files for each of the sites. The highest quality sites were selected and used to obtain the 2-D inverted sections for each of the four profile lines. The data and the match to the model are presented for each profile line in the Appendix to this report.

3.2.2 Frame Configuration

The deep ocean version of the MMT24 logger was modified for the specific requirements of this project: a new version of the deployment frame was implemented for shallow sites deployments. In this frame the digital acquisition system, power supply, dipoles and magnetic sensors were all mounted on a flat panel which could sink and have a very low profile for shallow water depths. Four of the modified systems loaded on the pontoon boat, ready for transport to their marine deployment site, are shown in Figure 7. Note that the electrode arms hinge upwards for travel and are extended horizontally to yield eight meter electrode separation at deployment. A reflective color buoy was attached in order to alert their presence to any water traffic. Sand bags were used to provide additional weight and prevent noise on the data due to the loggers' motion. In the electric dipoles arms the electrodes were molded to the cables carrying the signal to the logger. This modification was implemented for noise reduction purposes.

Figure 7: MMT24 marine systems-modified for shallow water deployment. (Schlumberger)

3.2.3 Deployment

Deep operation marine systems were deployed for water depth greater than five meter, while the modified frames were used on the shallower sites. Before deployment each system was synchronized with the GPS while assembling them on shore. After synchronization the high precision clock 10 MHz clock on the system takes over keeping absolute time to perform simultaneous acquisition and data processing with the data collected at the distant remote reference sites. The state of health of each MMT system was check by inputting a known signal to all the channels and running visual diagnostics using real time quality control software developed for this project.

An acquisition schedule was configured to run continuous low frequency acquisition (6 low frequency channels) and simultaneously record burst of high frequency data, both at 500 Hz and 50 Hz sampling, running for five and 30 min respectively, at intervals of 8 hours. The same acquisition schedule run at the reference sites, this allowed for unattended data acquisition running synchronously at multiple MT sites, on multiple frequency bands. In average 4-5 systems were carried out on the boat and deployed at the sites on each boat run, resulting in a rough deployment statistic of ~ ten sites per day. For the early marine survey trials the pontoon boat with a rigid roof was used (Figure 8), which provided a very convenient and pleasant area to work out of the sun, however the layout allowed only three systems to be loaded onto the boat. Depending on weather conditions the systems were recovered after a day of data acquisition. The data was retrieved from the storage device (on board 512 Mbyte flash card) using a custom made data download devise. This device was implemented specifically for this project in order to avoid opening the data acquisition pressure case and expose the electronic components of to the harsh environment conditions of the site.

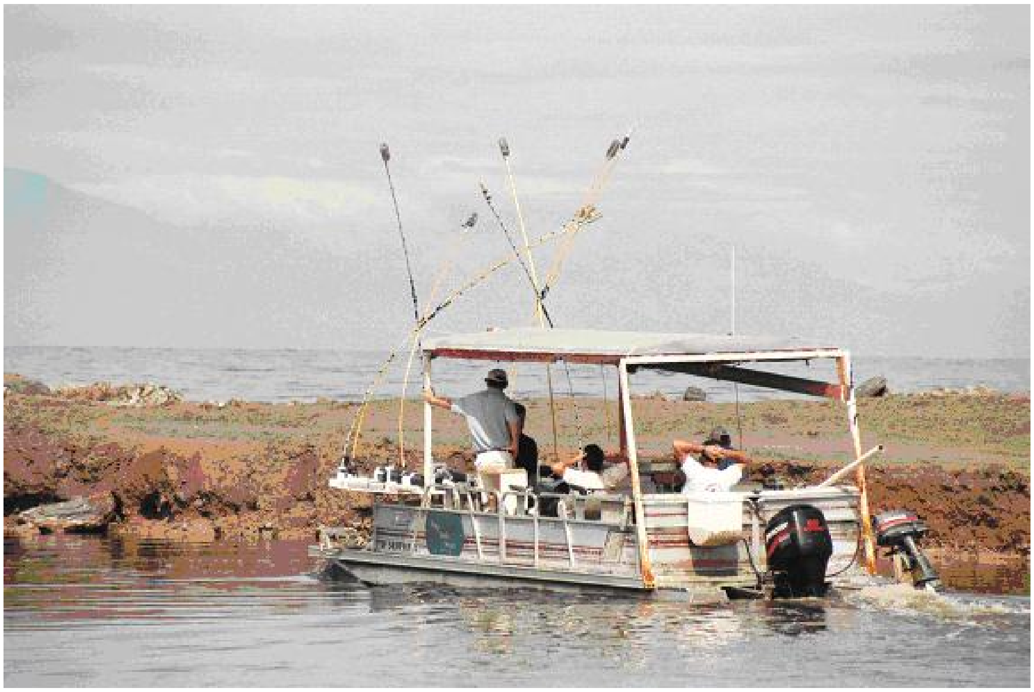

Figure 8: Two MMT24 marine systems loaded on the pontoon boat leaving to be deployed. **(Schlumberger)**

3.2.4 Marine Survey

Earlier survey attempts by Schlumberger had difficulty in obtaining good quality data and each site required a considerable amount of effort to setup the instruments, check it out and then recover the system and data. The data was recovered by bringing the instruments back to shore and opening up the instruments inside a base trailer setup at Obsidian Butte. This cumbersome method of handling the instruments contributed to errors in setting up instruments properly.

The problems identified in 2004 surveys were:

- Spikes introduced from hourly running of simultaneous high frequency data runs at 500 and 50 Hz. Each time the High Frequency (HF) A/D converter power interference signal showed up on the magnetic channels.
- Very low E signals (high ground conductivity and low signal levels) or broken electrical contacts on E signal cables.
- Intermittent E measurement failure, intermittent H measurement failure (cut wires on E, corroded E connectors).
- Water motion noise due to weather conditions (strong wind induced waves).

Data recovery was scheduled every two days in order to have all systems overlap acquisition for at least one whole day. To transfer the equipment from site to site: a system was opened, the data was extracted, the instrument was redeployed at another site, and finally the data was sent to the processing center (in Brawley). Therefore, nothing was known about a faulty measurement before the system was recovered the second time.

For the 2005 survey, the HF acquisition schedule was modified to launch only one additional HF band measurements per eight hours to reduce interference to the low frequency simultaneous measurements.

New software supporting live transfer of the data from the acquisition to a laptop PC was developed. This allowed the user to have a graphical display of the data as it was being collected, which enabled verification of operation of the acquisition system and allowed many types of errors in the setup to be caught before deploying the system. In addition, a high speed link was developed that allowed the data to be sent out of the system using an eight bit parallel data protocol into the PC. This allowed typical data transfer rates of 235 Kbytes/sec; which permitted 128 Mbytes of data to be downloaded in nine minutes. All of these software and hardware improvements were ready for Q1 2005 when Schlumberger went to the Salton Sea to acquire the marine survey data.

A pontoon boat, operated by Newton Wright of Ray's Salton Sea Guide Service, was engaged for the 2005 season. The same deployment method developed in 2004 for the marine surveys was used. Forty-three marine sites were occupied during the marine phase. Schlumberger personnel received excellent assistance from the NWR and DFG personnel. Inclement weather with high winds during part of the survey caused high wave motion, which reduced the data quality at eight of the sites; however thirty-five of the sites had good initial quality assessments. There were some occasional problems with individual channels, such as noisy electrode or H channel, however, the assessment made in the field was that the data were of acceptable quality and that robust remote reference processing would provide interpretation grade data. Two distant remote sites were recorded for the entire survey: sites RR6 and RR8 from the previous land survey phase. All of the data was backed up from the field computers and personnel returned to Schlumberger.

3.2.5 Land Survey

Six MT24LF systems were used for the land operations. Two were deployed at fixed remote reference sites (labeled as RR6 and RR8 in Figure 9) while the other four instruments were moved across the survey area. A total of 21 land sites were occupied through the survey. Table 1 gives the detailed position of each site. Figure 10 shows the position of the local sites, along with the position of the sites occupied during the September test, and the initial phase of the land survey in December 2003.

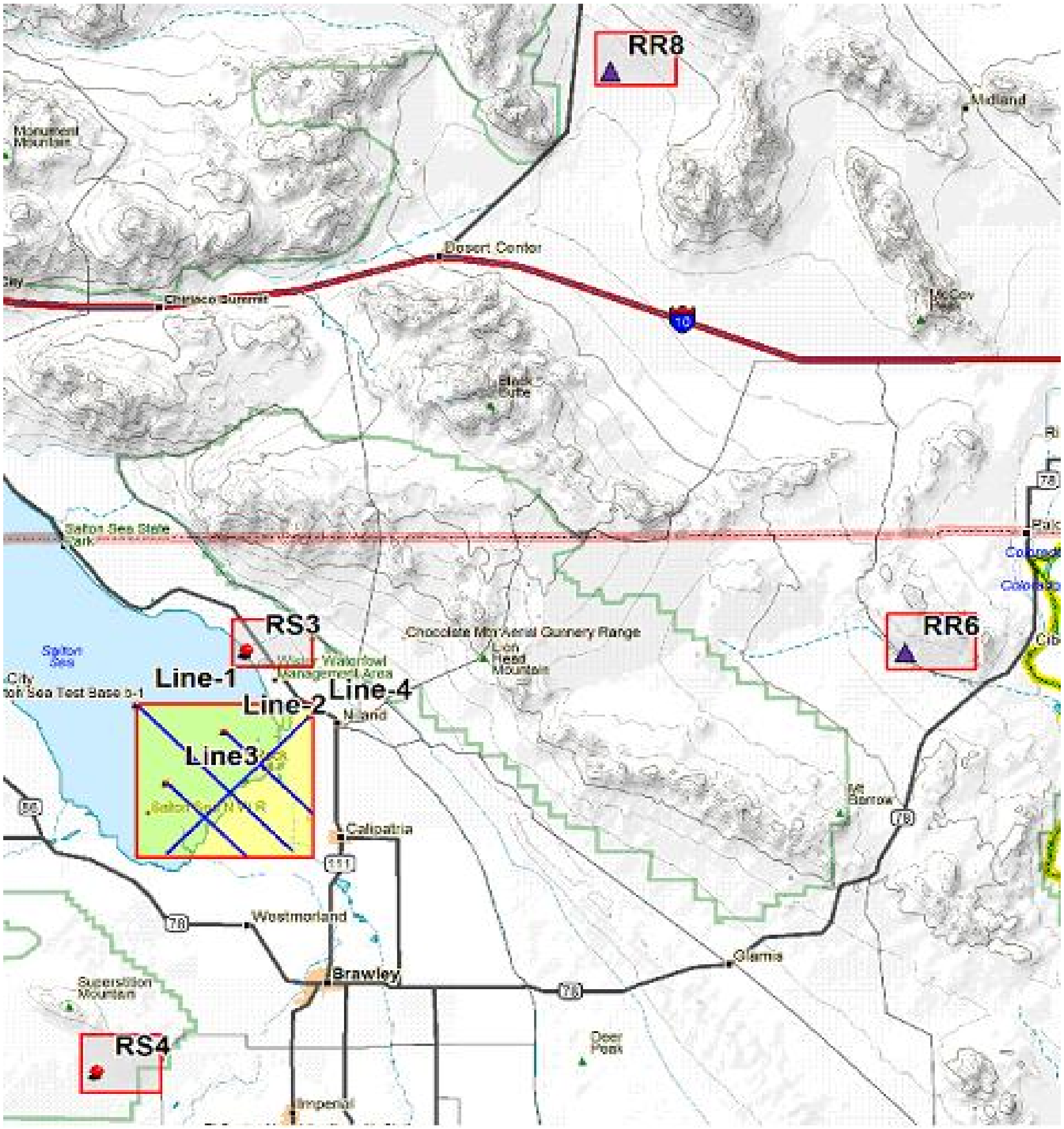

Figure 9: Survey location and location of remote reference sites for the survey. **(Schlumberger)**

Table 1: Land Sites - Detailed Position Information

Site ID	LAT	LONG		Site ID	LAT	LONG
RR6	N33 19.365	W114 52.302		L3-61S	N33 6.46002	W115 36.96
RR8	N33 54.542	W115 12.467		L4-00W	N33 7.23702	W115 39.9
L1-8S	N33 9.99198	W115 38.217		L4-10W	N33 7.69098	W115 39.927
L1-52SR	N33 8.16702	W115 35.88798		L4-20W	N33 8.691	W115 39.174
L1-60SR	N33 7.752	W115 35.805		L4-30W	N33 9.11598	W115 38.736
L1-70S	N33 7.026	W115 35.26602		L4-50W	N33 10.43202	W115 37.57698
L1-80S	N33 6.78	W115 34.653		L4-60W	N33 10.968	W115 37.392
L2-4S	N33 11.64	W115 35.80698		L4-115W	N33 12.74142	W115 35.15268
L2-8S	N33 11.253	W115 35.307		L4-120W	N33 12.97098	W115 35.00298
L2-12SR*	N33 10.85202	W115 34.731		L4-138ER*	N33 13.593	W115 34.32102
L2-16SR*	N33 10.39998	W115 34.2		L4-70W	N33 10.971	W115 36.843
L2-80S	N33 8.808	W115 32.58498				

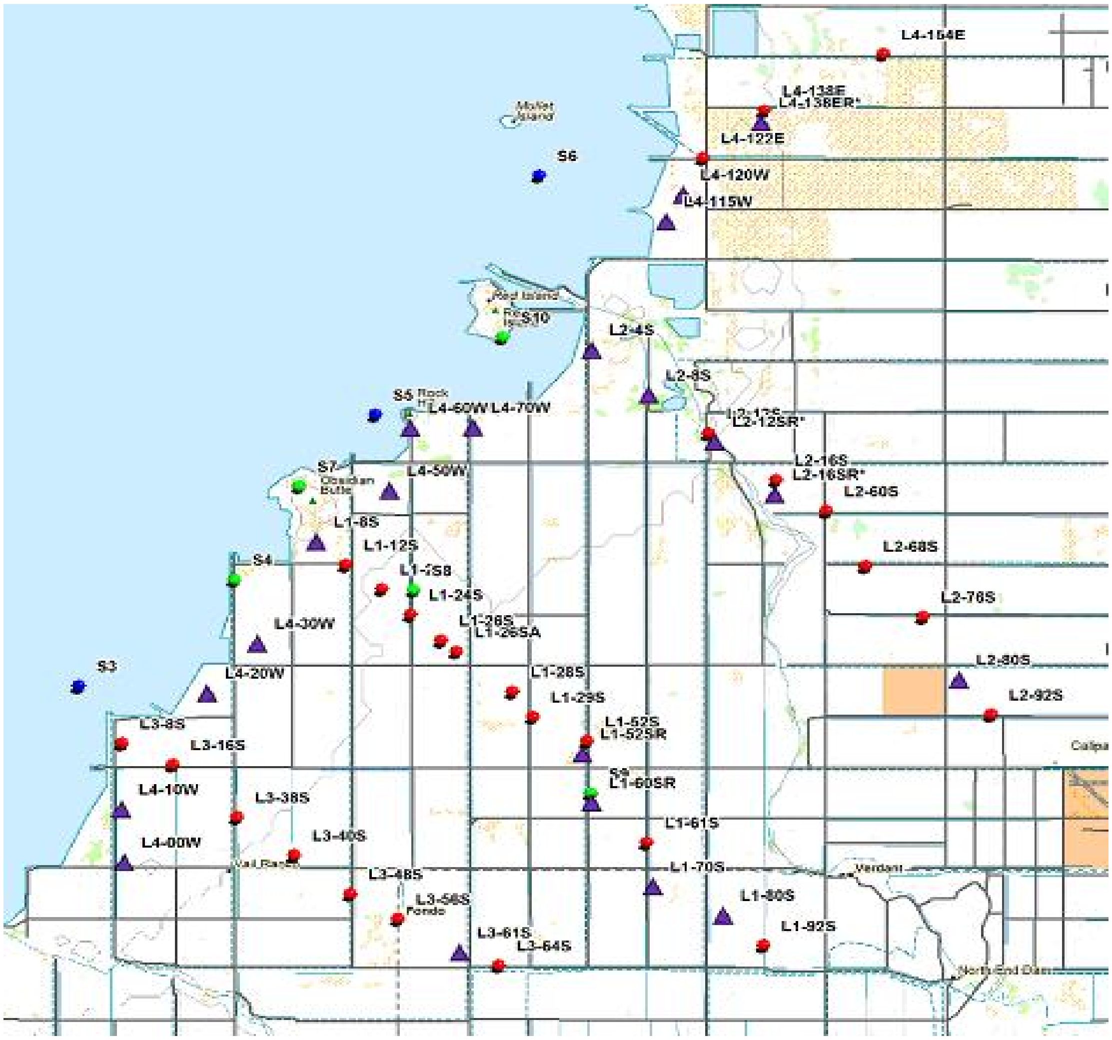

Figure 10: Detailed site location September 2003(,), December 2003 (, and March 2004 ( ) (Schlumberger)

Electric measurements were done using ~ 200 m electric dipoles on Cu-CuSO4 electrodes. Magnetic measurements were done using Schlumberger induction sensors, BF4 and BF7 type (frequency response: 0.001 to 1000 Hz). For convenience (due to the existing alignment of the local streets) sensor and dipole orientation at each site was chosen east, as the positive X component. The sites occupied September and December 2003 were also aligned on the same direction.

Two remote reference sites were installed: RR6, located about 43 miles away from the local survey and RR8, located about 57 miles from the survey. The remote reference site was used in the processing to identify the MT signals which were simultaneously present at the main survey area. The remote sites were chosen so that they were not contaminated by man-made signals or other environmental noise. These sites were located far enough away from the Salton Sea Survey to ensure that these sites were not contaminated by man-made electromagnetic signals originating in or near the survey area.

Acquisition was configured on dual batch mode: Low Frequency (LF) A/D converters were configured to record data continuously with a 6.25 Hz sampling rate while the HF A/D converters were configured to periodically turn ON/OFF, recording short bursts of 500 Hz and 50 Hz data. This mode of operation was called scheduled batch mode.

The remote reference sites were run unattended, using an hourly repeating HF schedule to provide maximum HF data redundancy. HF data collection consisted of five minutes of 500 Hz data and then 30 minutes of 50 Hz data.

On average, data acquisition continued for ~1.8 days at each site.

3.3 Data Processing and Interpretation

3.3.1 Data Processing to Produce MT Parameters

Data processing for the survey consisted of the following steps:

1. The data was downloaded from the Flash memory using the download unit connected by cables to the PC and MMT24. This data transfer method was carried out on the open deck of the pontoon boat used in the system deployment and recovery and replaced the earlier cumbersome method of opening the MMT24 acquisition pressure vessel and removing the Compact Flash memory card.
2. The downloaded data was converted from 24 bit binary format to 32 bit integer fixed record blocks for fast data reading by the processing programs.
3. The software program ACQ24 was used to review the data and align the different sites acquisition bands with remote sites (see Figure 11).

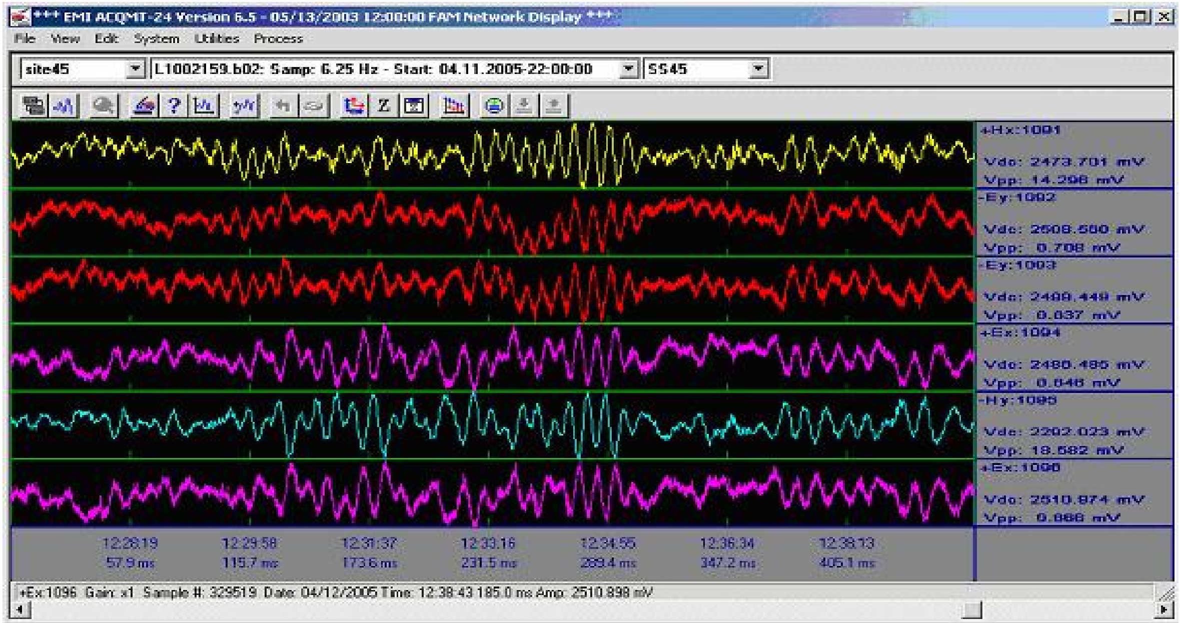

Figure 11: Reviewing the data and aligning the different site acquisition bands. **(Schlumberger)**

4. The MT workstation program LMMT_XP was used to compute MT spectral parameters for each of the receiver sites (see Figure 12). This step was an iterative one that required careful attention to the rotation, timing and types of noise on each recorded channels. There were several types of noise reduction techniques that were evaluated to ensure optimum processing of the time series data. This process was generally known as robust remote reference processing.

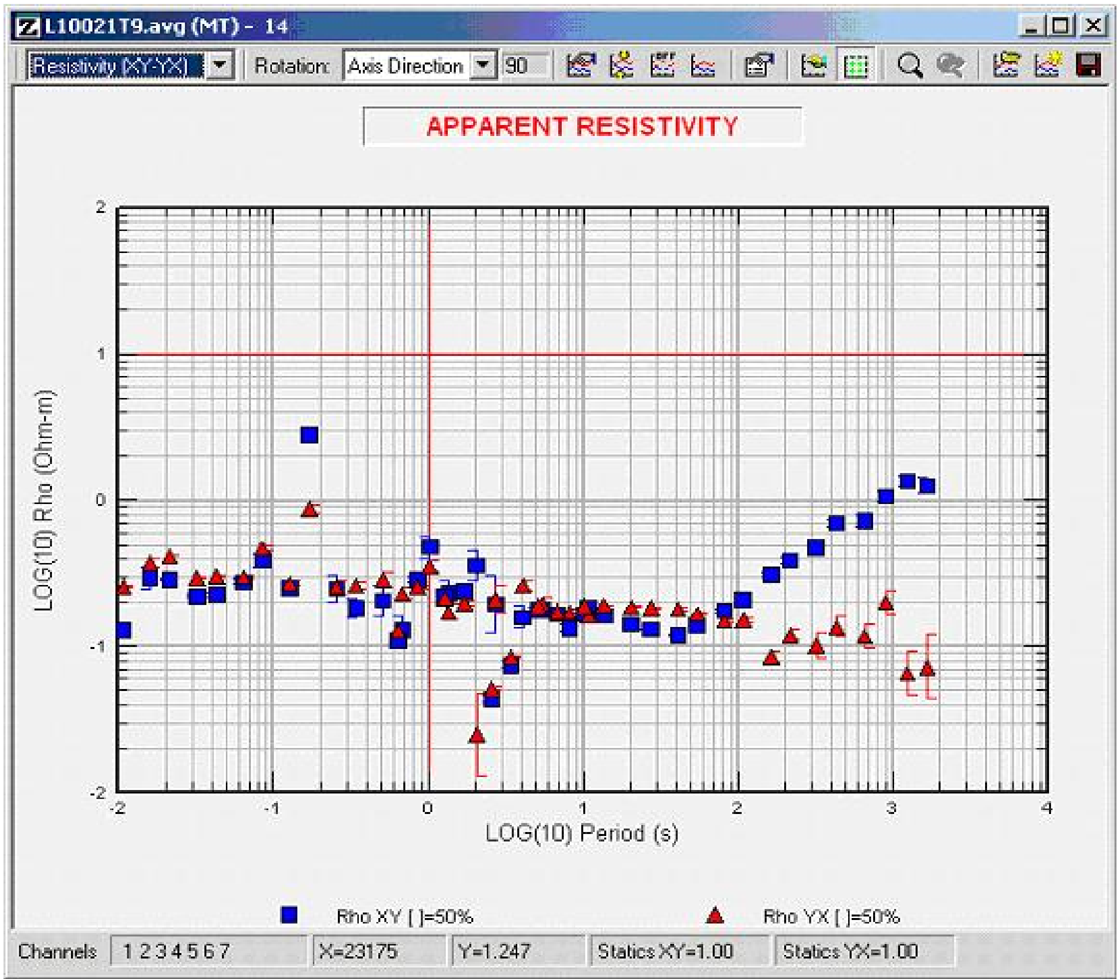

Figure 12: MT Spectral Parameters. **(Schlumberger)**

5. The robust remote referenced MT data for each site was assembled into profiles using the site's GPS coordinates to determine their spacing along the profile line. Rotation of the marine sites was necessary to align the low frequency impedance polar diagrams with the land sites.
6. The program MTWorks and GEM, both developed by Hoversten[15], was used to invert the MT profiles and obtain resistivity versus depth profiles. Two dimensional inversions were done using the electric field measured along the profile and assuming this was the TM mode. Note that a thin superficial layer of 0.2 ohm meters was used for the known bathymetry of the Salton Sea.

3.3.2 Data Interpretation to Produce Final Resistivity Sections

As one of the data processing steps required to complete the MMT survey at the Salton Sea, MT 2D inversions were carried out using MTWorks - a software package for MT data processing and inversions (Hoversten [15]).

3.3.2.1 Coordinate Conversion

The original coordinates for each MMT site were in latitude and longitude. This is an appropriate format for displaying the MMT locations using Google's Earth. Tiziano Labruzzo (Schlumberger) generated the MMT survey map, as shown in Figure 13, with this format.

Figure 13: Survey map for the MMT at the Salton Sea Geothermal Field, California. (Schlumberger)

However, in the MT inversion, a Cartesian coordinate system was needed. Therefore, it was necessary to convert the latitude/longitude coordinates into Universal Transverse Mercator (UTM) coordinates. GEO_CON of Son of Wolf Enterprise was used to do the conversion. GEO_CON can be freely downloaded from its website. See http://rockyweb.cr.usgs.gov/software/geocon.readme. The coordinates were converted to NAD83 UTM (zone 11, 114W to 120W). Table 2 lists coordinates for each site in both systems.

Table 2: Coordinates for each MMT site at the Salton Sea (Schlumberger)

No. Site	Profile Line Site	Lat (deg min sec)	Long (deg min sec)	UTM_X	UTM_Y
1	L1-12S	33 09 43.14	115 37 57.30	627509.34	3670077.07
2	L1-20S	33 09 30.54	115 37 38.40	628004.02	3669695.41
3	L1-24S	33 09 17.40	115 37 23.10	628405.69	3669295.91
4	L1-28S	33 08 37.74	115 36 29.70	629805.32	3668092.71
5	L1-29S	33 08 24.60	115 36 18.78	630093.64	3667691.78
6	L1-60S	33 07 45.12	115 35 48.30	630899.69	3666486.38
7	L1-61S	33 07 19.98	115 35 19.14	631665.77	3665722.24
8	L1-92S	33 06 26.88	115 34 17.64	633281.90	3664108.41
9	L1-27S	33 08 48.90	115 36 39.48	629547.37	3668433.07
10	L1-52S	33 08 10.02	115 35 53.28	630760.38	3667251.55
11	L1-70S	33 07 01.56	115 35 45.96	630978.29	3665145.69
12	L1-80S	33 06 54.30	115 35 39.18	631157.01	3664924.35
13	L1-08S	33 09 59.52	115 38 13.02	627095.56	3670576.24
14	L2-60S	33 10 10.80	115 33 44.52	634046.08	3670994.49
15	L2-68S	33 09 42.42	115 33 23.82	634594.00	3670149.97
16	L2-76S	33 09 16.14	115 32 53.70	635385.47	3669351.35
17	L2-92S	33 08 25.92	115 32 17.94	636333.48	3667817.49
18	L2-04S	33 11 38.40	115 35 52.20	630702.43	3673669.82
19	L2-08S	33 11 15.18	115 35 18.42	631586.81	3672966.43
20	L2-12S	33 10 50.94	115 34 46.50	632423.57	3672231.04
21	L2-16S	33 10 24.00	115 34 12.00	633328.43	3671413.47
22	L2-80S	33 08 48.48	115 32 35.10	635879.19	3668506.13
23	L3-08S	33 08 11.04	115 39 54.72	624503.81	3667201.27
24	L3-16S	33 07 60.00	115 39 27.84	625204.67	3666869.85
25	L3-38S	33 07 32.88	115 38 54.42	626081.44	3666046.03
26	L3-40S	33 07 13.38	115 38 24.30	626869.79	3665455.55
27	L3-48S	33 06 53.34	115 37 54.72	627644.45	664848.32
8	3-56S	33 06 40.62	115 37 29.76	28296.51	664465.02
9	3-64S	33 06 16.50	115 36 36.66	29982.66	663740.30
0	3-61S	33 06 27.56	115 36 57.54	29136.93	664073.78
1	4-122E	33 12 12.72	115 34 49.44	32313.26	674748.77
2	4-138E	33 13 37.32	115 34 17.28	33110.36	677365.73
3	4-00W	33 07 14.22	115 39 54.00	24544.75	665451.54

4	4-10w	33 07 41.46	115 39 55.62	24492.08	666289.96
5	4-115E	33 12 45.30	115 35 12.12	31712.46	675744.26
36	L4-154E	33 14 06.18	115 33 14.52	634722.64	3678276.94
37	L4-30W	33 09 06.96	115 38 44.16	626309.87	3668946.99
38	L4-50W	32 10 25.92	115 37 34.62	628079.56	3671402.33
39	L4-60W	33 10 58.08	115 37 23.52	628354.03	3672396.60
40	L4-95W	33 11 48.12	115 36 31.56	629679.22	3673955.59
41	SSx01	33 15 35.22	115 44 50.58	616073.84	3680786.68
42	SSx03	33 14 22.08	115 43 25.50	618902.81	3678560.71
43	SSx04	33 13 45.54	115 42 48.72	619868.57	3677446.99
44	SSx08	33 11 30.24	115 40 05.58	624144.38	3673332.79
45	SSx09	33 11 16.02	115 39 42.66	624746.09	3672902.43
No. Site	**Profile Line Site**	**Lat (deg min sec)**	**Long (deg min sec)**	**UTM_X**	**UTM_Y**
46	SSx10	33 10 59.40	115 39 21.54	625297.01	3672397.53
47	SSx11	33 10 38.40	115 38 57.00	625940.89	3671758.94
48	SSx12	33 08 46.92	115 40 16.86	623916.11	3668299.03
49	SSx13	33 09 22.26	115 39 33.90	625015.22	3669401.64
50	SSx14	33 09 44.10	115 39 07.86	625681.15	3670082.94
51	SSx15	33 10 12.90	115 38 12.90	627093.30	3670988.37
52	SSx16	33 10 45.24	115 37 51.96	627622.66	3671991.49
53	SSx17	33 11 14.16	115 37 34.86	628053.85	3672887.99
54	SSx19	33 07 53.34	115 41 07.20	622632.57	3666632.40
55	SSx20	33 08 27.60	115 40 41.40	623287.82	3667695.97
56	SSx21	33 08 35.76	115 40 27.66	623640.64	3667951.78
57	SSx28	33 11 20.76	115 37 13.50	628604.33	3673098.54
58	SSx29	33 10 54.90	115 37 43.92	627826.99	3672291.73
59	SSx31	33 09 58.08	115 38 51.54	626098.35	3670518.96
60	SSx32	33 09 29.52	115 39 25.98	625217.53	3669627.87
61	SSx34	33 09 02.22	115 40 36.60	623398.72	3668763.78
62	SSx35	33 09 20.22	115 40 58.38	622827.49	3669311.03
63	SSx36	33 09 39.72	115 41 22.74	622188.90	3669903.70
64	SSx39	33 10 33.78	115 42 26.40	620519.28	3671548.17
65	SSx40	33 10 51.54	115 42 48.72	619934.47	3672088.03
66	SSx41	33 12 40.08	115 37 16.80	628486.68	3675540.40
67	SSx42	33 12 59.10	115 37 39.36	627894.91	3676118.51
68	SSx43	33 13 19.38	115 38 03.54	627260.77	3676734.92
69	SSx44	33 13 38.28	115 38 26.58	626656.78	3677309.25
70	SSx45	33 13 57.84	115 38 49.98	626043.27	3677903.83

Of the 70 MMT sites, there were 40 land sites (indicated with capital letter 'L') and 30 marine sites (indicated with 'SS'). These sites were grouped into four profiles lines as shown in Figure 3. Lines 1, 2, and 3 were roughly parallel to the geologic strike direction. Line 4 ran perpendicular to the geologic strike direction.

3.3.3 Rotating Impedances Into Principal Directions

The next step was to rotate the impedances to a principal direction, in order to have two independent modes (TE/TM). This was done within LMMT_XP, a software package developed by Zerilli (Schlumberger). The data used were in EDI format. Labruzzo (Schlumberger) performed all the data processing and generated the EDI files from recorded time series data.

Land MT sites

For land MT sites, the rotation was straightforward. In this case, the exact orientations of both electrical and magnetic sensors were known. Figure 14 shows the Impedance Polar plots for each frequency of site L4-10W.

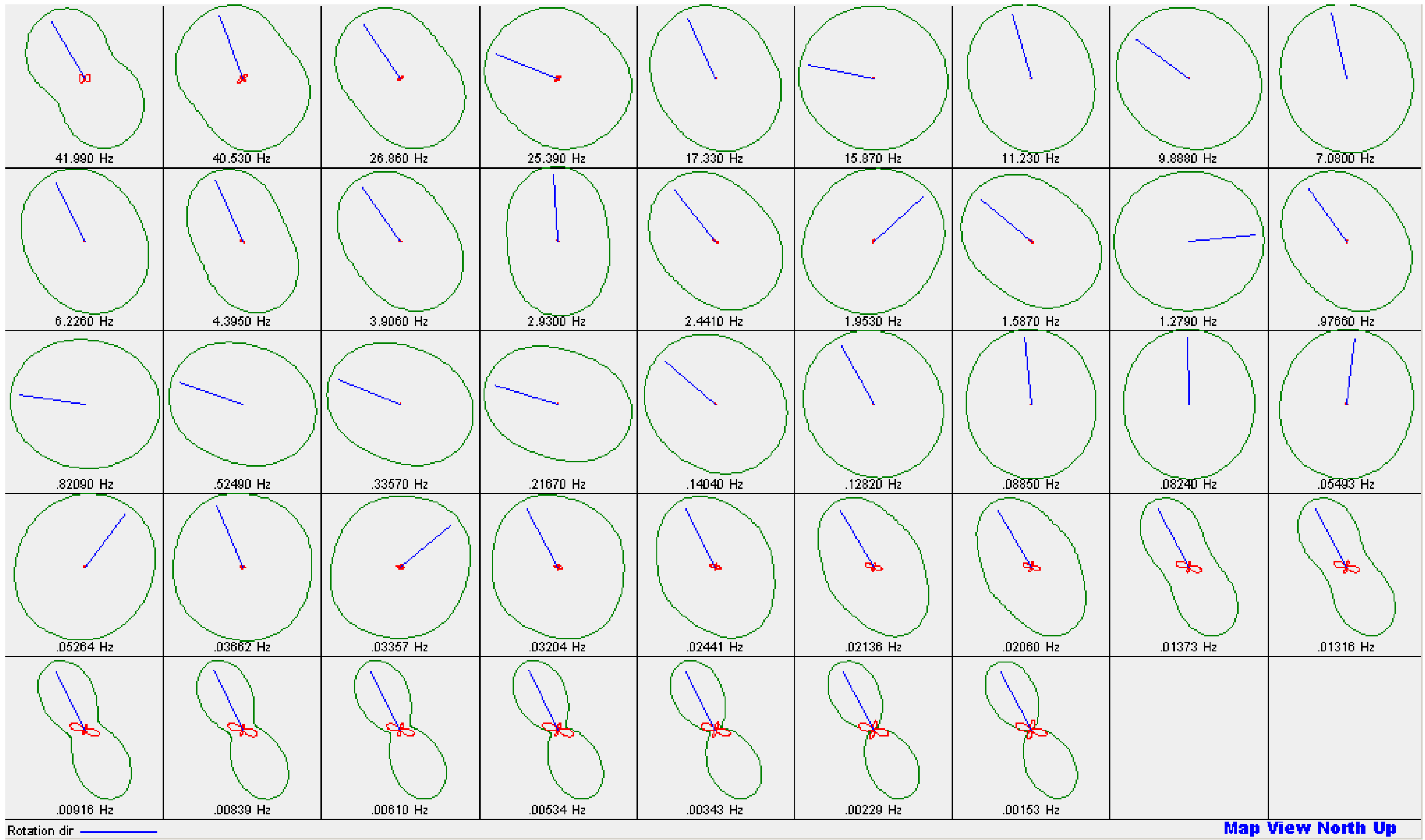

Figure 14: Impedance Z polar diagram at site L4-10W (Schlumberger)

Usually the principal direction changed with the frequency, especially for medium to high frequencies. At the high frequency end, the Z polar looked more like a circle, rather than a dumb-bell, suggesting a 1D or 3D structure near the surface. But for low frequencies, in theory, there should have been a definite structure direction. When the frequency was less than 0.0137 Hz (or period is greater than 73s), the principal direction was obvious and stable, suggesting a strike direction that was consistent with a 2D large scale or regional structures, and this direction lined up with the mountain ranges and was parallel to the Salton Sea Trough. In this case, the strike angle was 332 degrees WNW.

For all the land sites, it was found that 325 degree was an averaged estimation of the strike direction (except site L4-60W, which had an angle of five degrees). Therefore, the impedances were rotated by a fixed angle of 35 degrees for all the frequencies to obtain the two mode data, shown in Figure 15. The upper panel contains the apparent resistivities (Rxy and Ryx), and the lower the impedance phases. Here, it was assumed that in Rxy the current flowed in the x direction (or strike direction) and the magnetic field in the orthogonal direction. By the same token, in Ryx the current flowed in the y direction (or orthogonal to the strike direction) and the magnetic field was in the strike direction. This was important, because it was needed to identify TE/TM modes in the following inversion. These apparent resistivity and phase data were output into a *.res file, which were loaded directly into MTWorks for inversion.

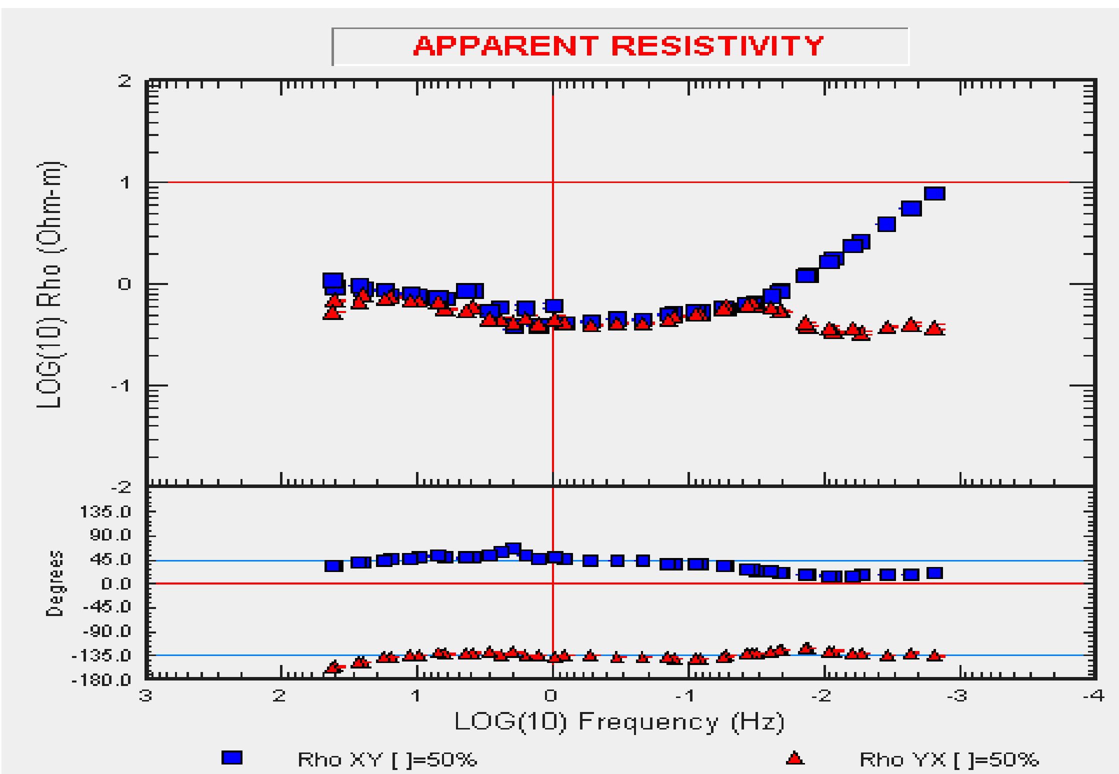

Figure 15: Apparent resistivities Rxy/Ryx and their phases at site L4-10W after rotation to its strike direction. **(Schlumberger)**

MMT Sites

For the MMT sites, it was not known how the electrodes and magnetic sensors were laid in the water. There was uncertainty of the system orientation. However, the Z polar diagram could still be plotted, by figuring out a strike direction using the lower frequency data. For example, at marine site SSx08, when frequency was below 0.00916 Hz (or period is greater than 100 s), the ‘principal direction’ was about 45 degrees. See Figure 16.

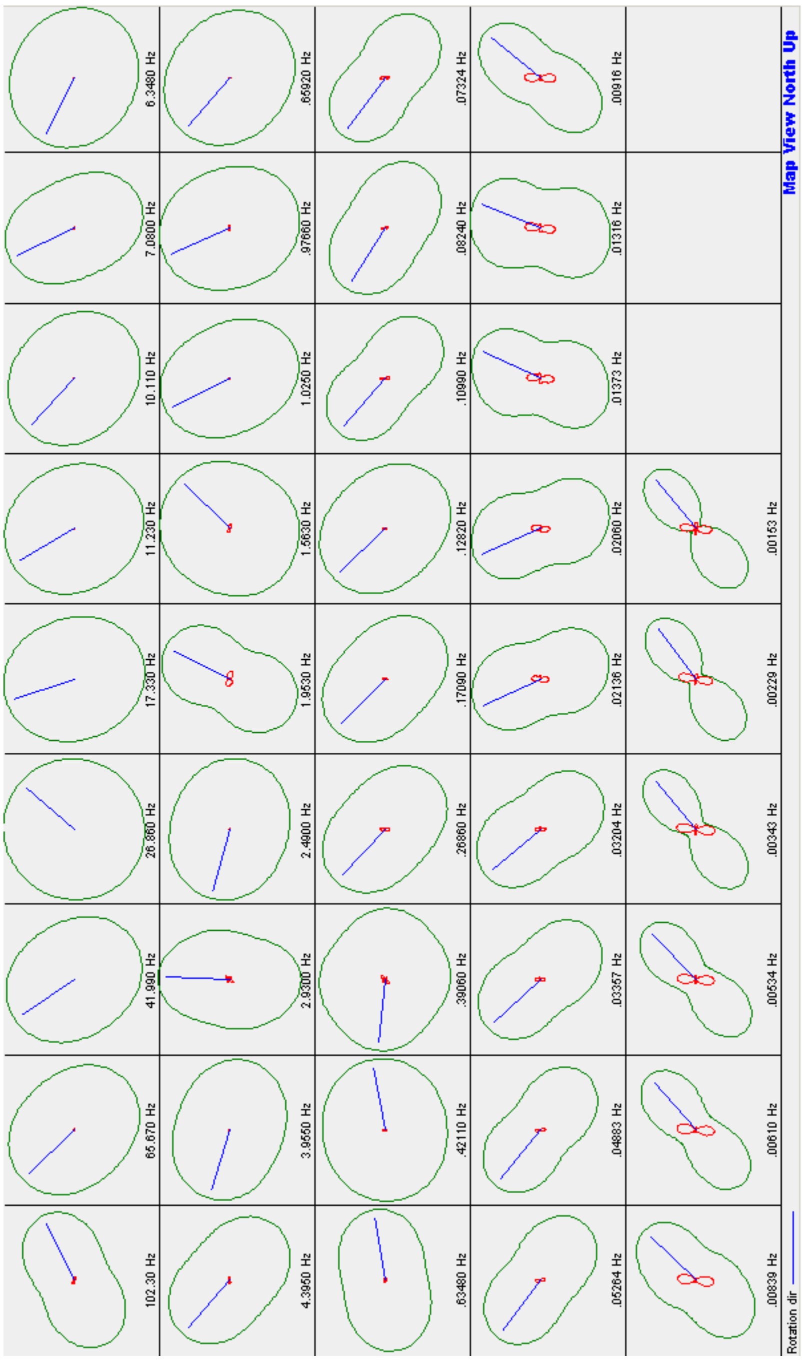

Figure 16: Impedance Z polar diagram at marine site SSx08. (Schlumberger)

Note that this angle did not have a physical meaning, because there was no reference direction. Different marine sites may have different 'strike directions', a fundamental difference compared to land MT sites. This is fine, as long as the impedances are rotated into these 'strike directions', the two mode data can still be obtained. This is shown in Figure 17, where after a rotation of 45 degrees for all the frequencies at site SSx08, the two apparent resistivites and impedance phases have been obtained.

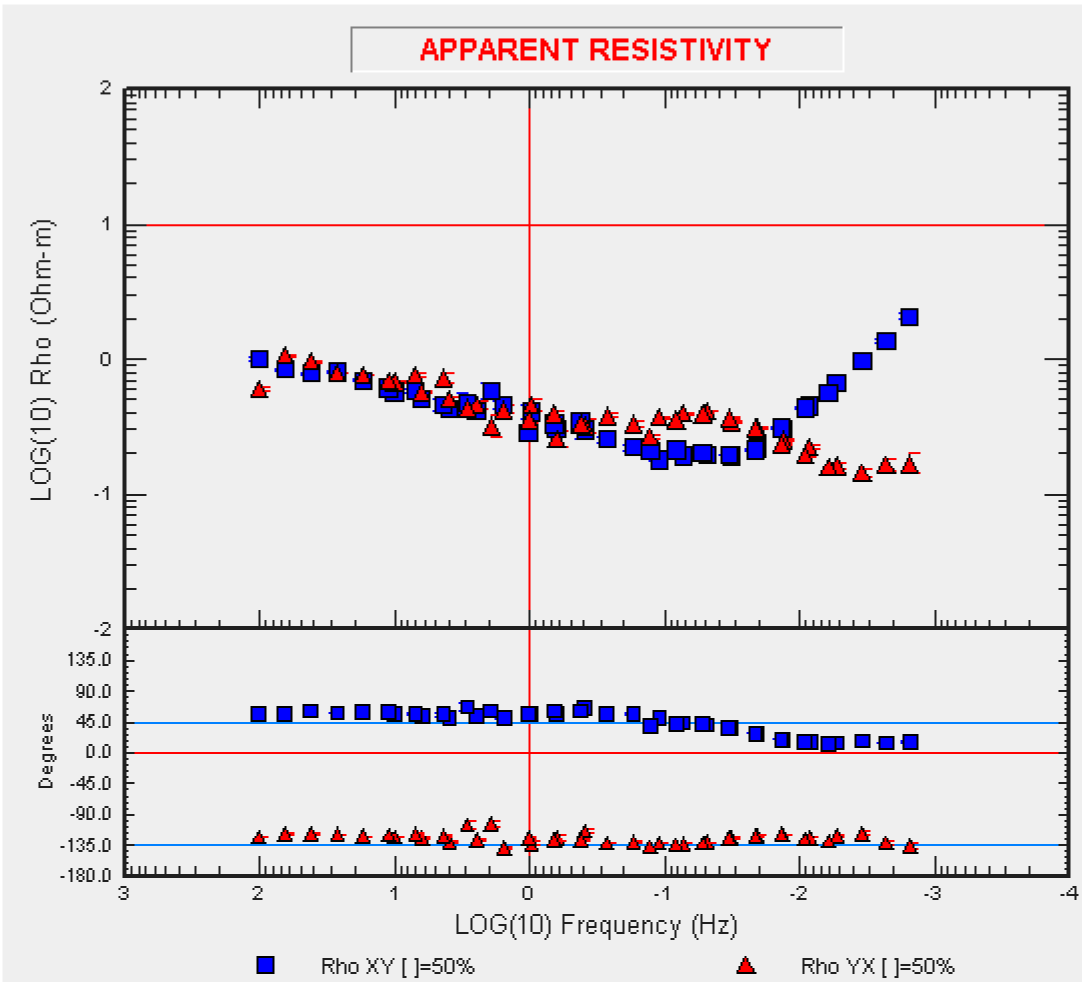

Figure 17: Apparent resistivities Rxy/Ryx and their phases at site SSx08 after rotation to its "strike direction". **(Schlumberger)**

Tie-up Land and MMT Sites

Table 3 lists the rotation angles for all the 70 sites. These angles were used to do the rotation and have the apparent resistivity's and phases computed.

Table 3: Site Rotation Angles **(Schlumberger)**

No site	Profile Line Site	Rotation Angle (degrees)		No site	Profile Line Site	Rotation Angle (degrees)
1	L1-12S	-35		36	L4-154E	-35
2	L1-20S	-35		37	L4-30W	-35
3	L1-24S	-35		38	L4-50W	-35
4	L1-28S	-35		39	L4-60W	-5
5	L1-29S	-35		40	L4-95W	-35
6	L1-60S	-35		41	SSx01	-50
7	L1-61S	-35		42	SSx03	-75
8	L1-92S	-35		43	SSx04	-5
9	L1-27S	-35		44	SSx08	45
10	L1-52S	-35		45	SSx09	90
11	L1-70S	-35		46	SSx10	-40
12	L1-80S	-35		47	SSx11	-20
13	L1-08S	-35		48	SSx12	-20
14	L2-60S	-35		49	SSx13	50
15	L2-68S	-35		50	SSx14	-70
16	L2-76S	-35		51	SSx15	25
17	L2-92S	-35		52	SSx16	40
18	L2-04S	-35		53	SSx17	-5
19	L2-08S	-35		54	SSx19	0
20	L2-12S	-35		55	SSx20	35
21	L2-16S	-35		56	SSx21	-70
22	L2-80S	-35		57	SSx28	-35
23	L3-08S	-35		58	SSx29	30
24	L3-16S	-35		59	SSx31	-80
25	L3-38S	-35		60	SSx32	0
26	L3-40S	-35		61	SSx34	-85
27	L3-48S	-35		62	SSx35	50
28	L3-56S	-35		63	SSx36	70
29	L3-64S	-35		64	SSx39	45
30	L3-61S	-35		65	SSx40	-45
31	L4-122E	-35		66	SSx41	-45
32	L4-138E	-35		67	SSx42	45
33	L4-00W	-35		68	SSx43	10
34	L4-10w	-35		69	SSx44	40
35	L4-115E	-35		70	SSx45	70

To make sure these rotations generated consistent results the computed apparent resistivities were compared at two close sites, one on land and the other in the water. Figure 18 shows the comparisons were reasonably consistent for both apparent resistivities Rxy and Ryx.

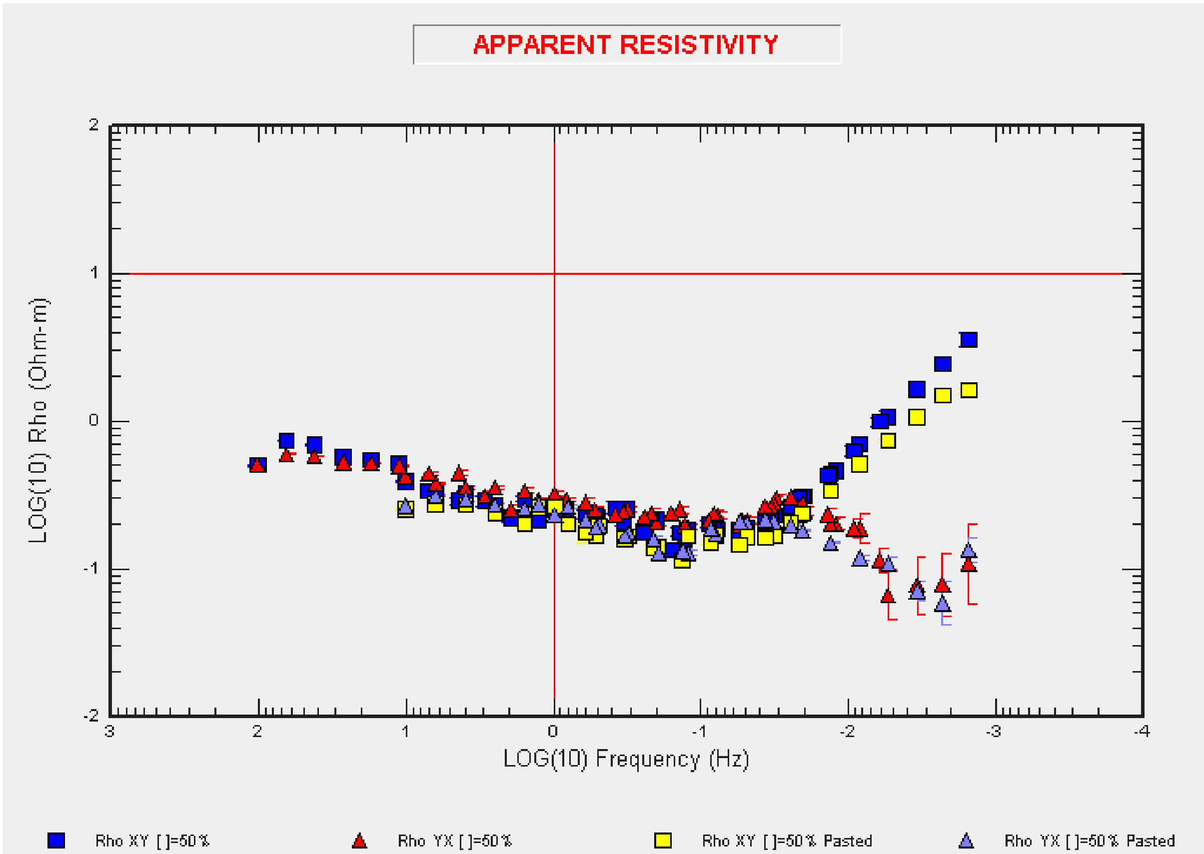

Figure 18: Comparison of apparent resistivities at sites L4-60w and SSx17. **(Schlumberger)**

3.3.3.1 2D MT inversions

Profile Line 1

Once the data was generated, the 2D inversions were carried out within MTWorks. To use this inversion, it was necessary to first define a "strike" direction where the geology did not vary. In MT this is denoted as the TE mode (see Figure 19). The orthogonal "dip" direction where geologic changes are allowed is the TM mode In general, the strike should conform to the regional basin strike of N45W but in this case the geothermal field trended orthogonal to this regional strike. Since the main targets of this study were variations in the geothermal field, strike, or TE mode, was defined as N45E.

Three of the Profile Lines 1, 2 and 3 trended N45W, orthogonal to this strike direction, and Line 4, established for regional geologic control, trended N45E.

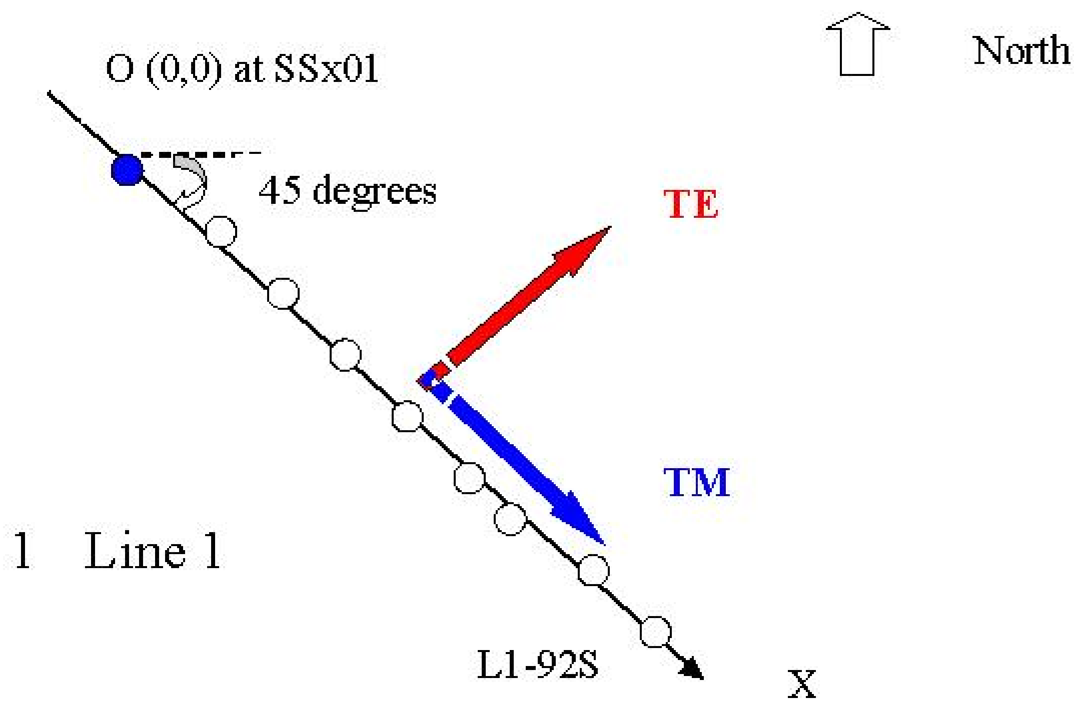

Figure 19: Layout of Profile Line 1 for 2D inversion. **(Schlumberger)**

Figures 20a shows the pseudo-sections of TM mode apparent resistivity for Profile Line 1, and Figure 20b show the TM impedance phase.

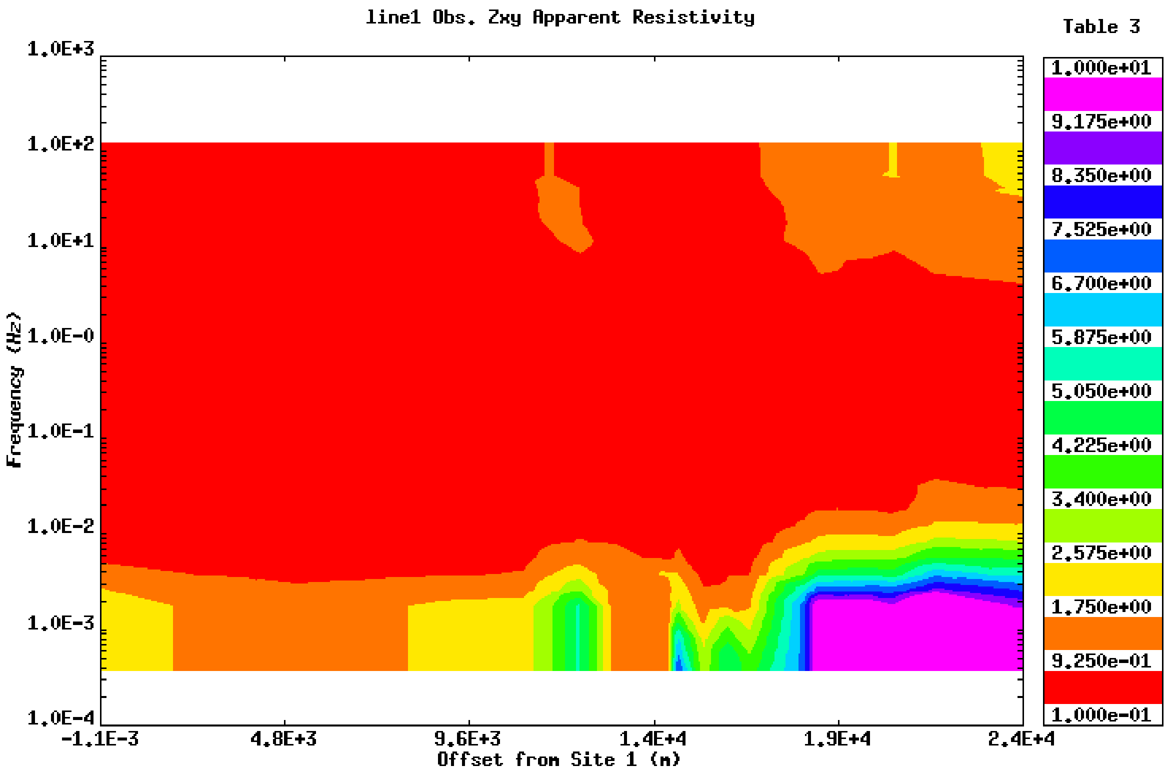

Figure 20a: The observed pseudo-section for (a) apparent resistivity Rxy along Profile Line 1.
(Schlumberger)

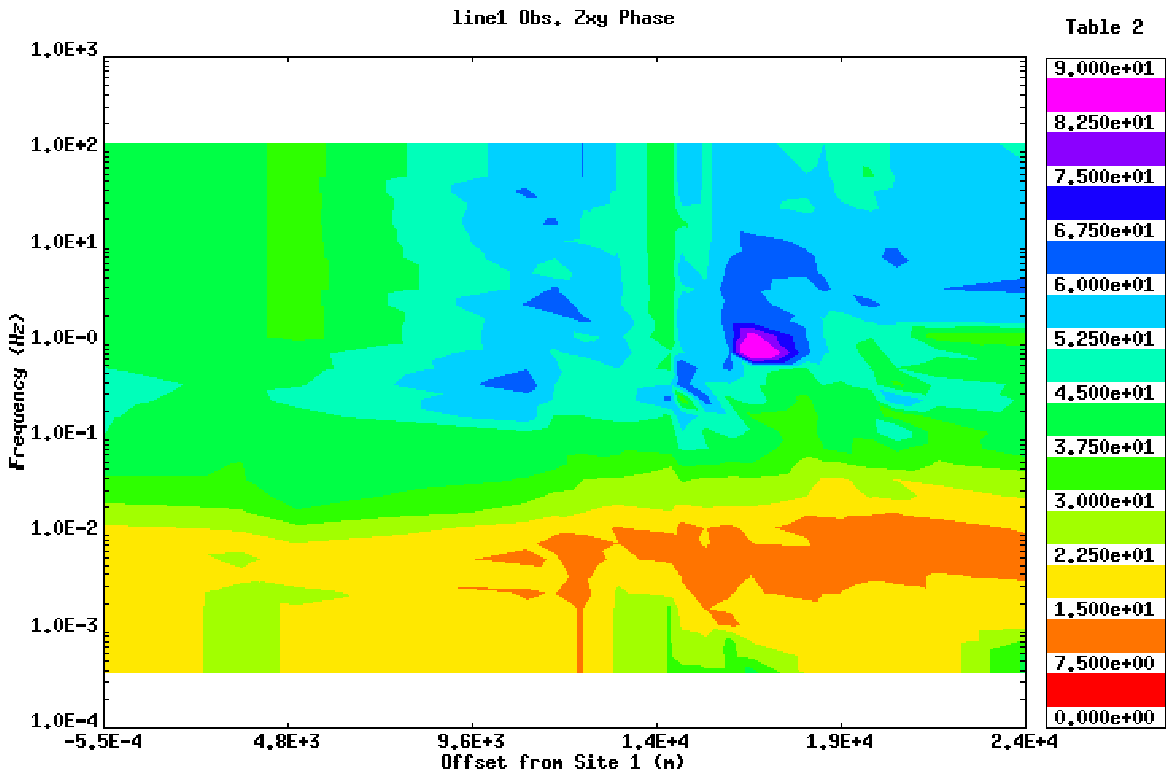

Figure 20b: The observed pseudo-section for Rxy, its phase along Profile Line 1. **(Schlumberger)**

After a bit of smoothing and editing, the data was ready. The noise level was assumed to be 7.5%. The initial model was a uniform half-space of 1.0 Ohm. Because Profile Line 1 included some marine sites, it was necessary to take into account the water layer, which was highly conductive. The salinity of the Salton Sea water was about 44,000 ppm, and the temperature was around 20 degree C when the data were collected. From these values, the water resistivity was calculated using an empirical formula. It turned out that the water resistivity was in the order of 0.15 Ohm.m. The water depth varied from 14.5 m at SSx01 to 2.0m at SSx15 near the shore. The whole 2D model was divided into 223x123 cells. After 45 iterations, a data misfit of 1.55 was reached. Figure 21 is the inverted 2D resistivity profile.

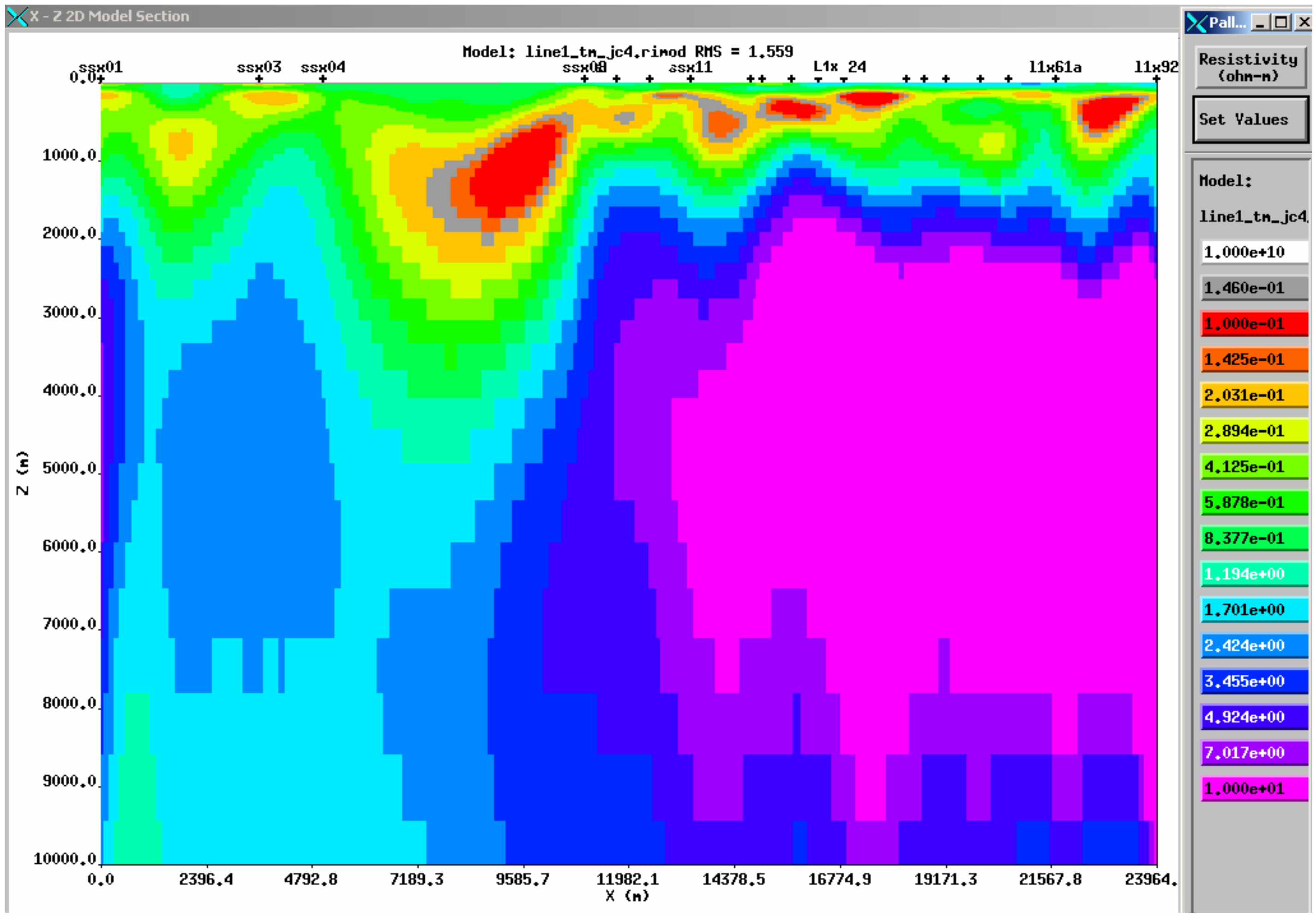

Figure 21: The inverted 2D resistivity profile along Line 1. (Schlumberger)

The comparison of observed and predicted apparent resistivity data is shown in Figure 22a and the impedance phase in Figure 22b. Generally, the data fit was reasonable.

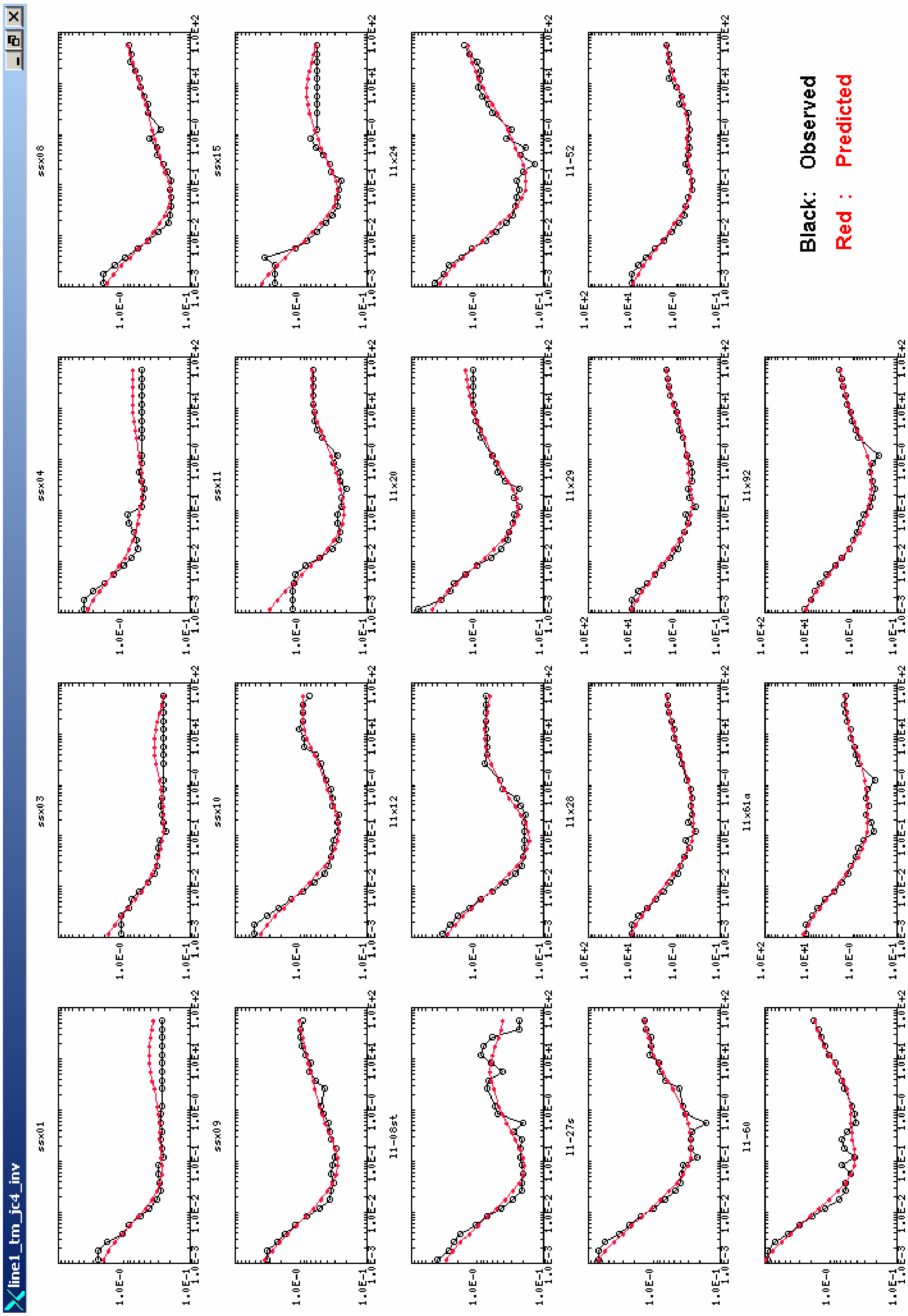

Figure 22a: Data fit along Line 1; apparent resistivity Rxy. (Schlumberger)

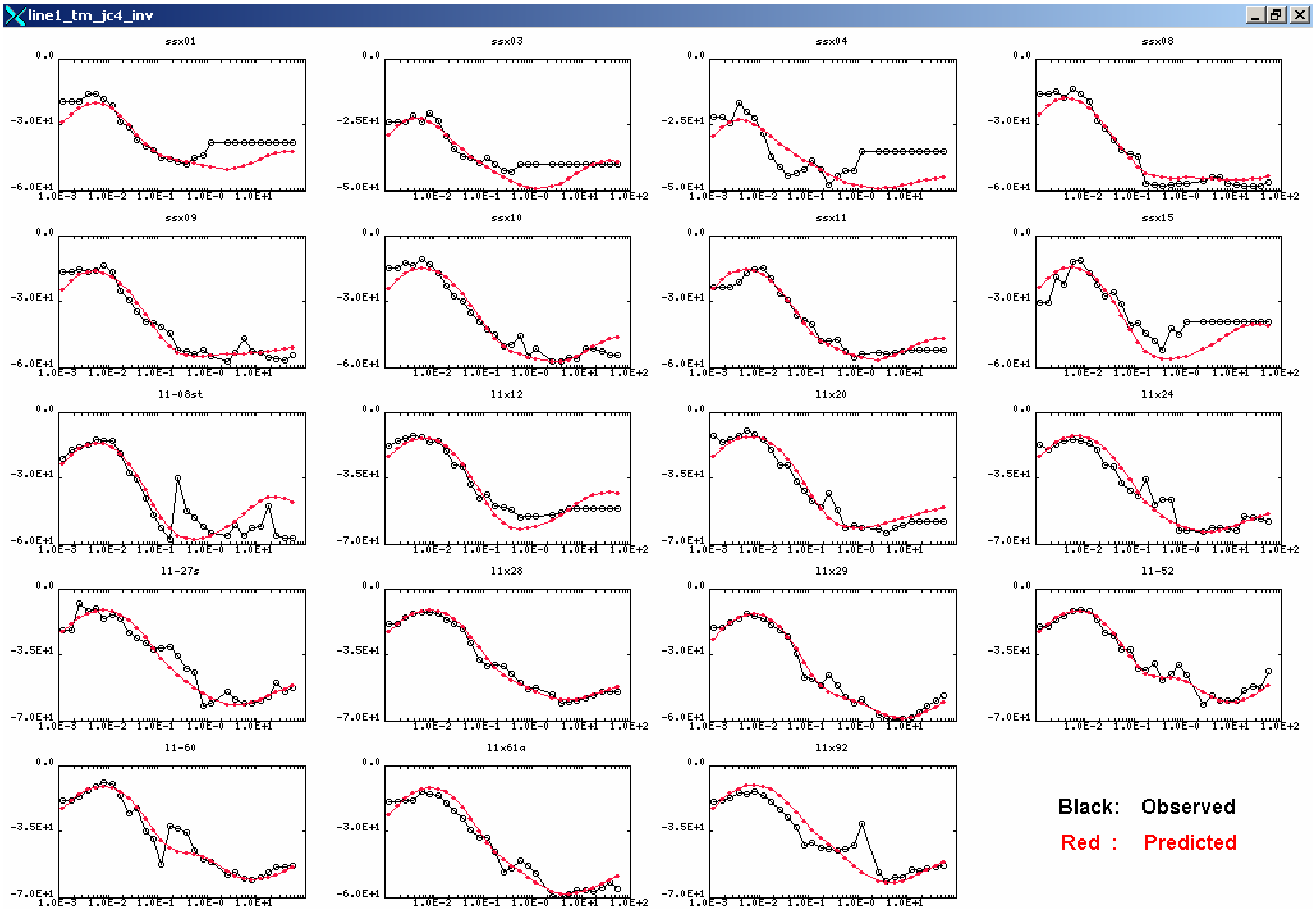

Figure 22b: Data fit along Line 1; its phase. **(Schlumberger)**

Profile Line 2

Similar procedures were performed here. The only difference was that the data at sites L2x16S and L2x60S was static-shifted down by a factor of four. The reason was that compared to the neighboring sites, the apparent resistivity, especially at high frequency, was obviously higher. The phase data were not affected by this shift.

The inverted resistivity image is shown in Figure 23.

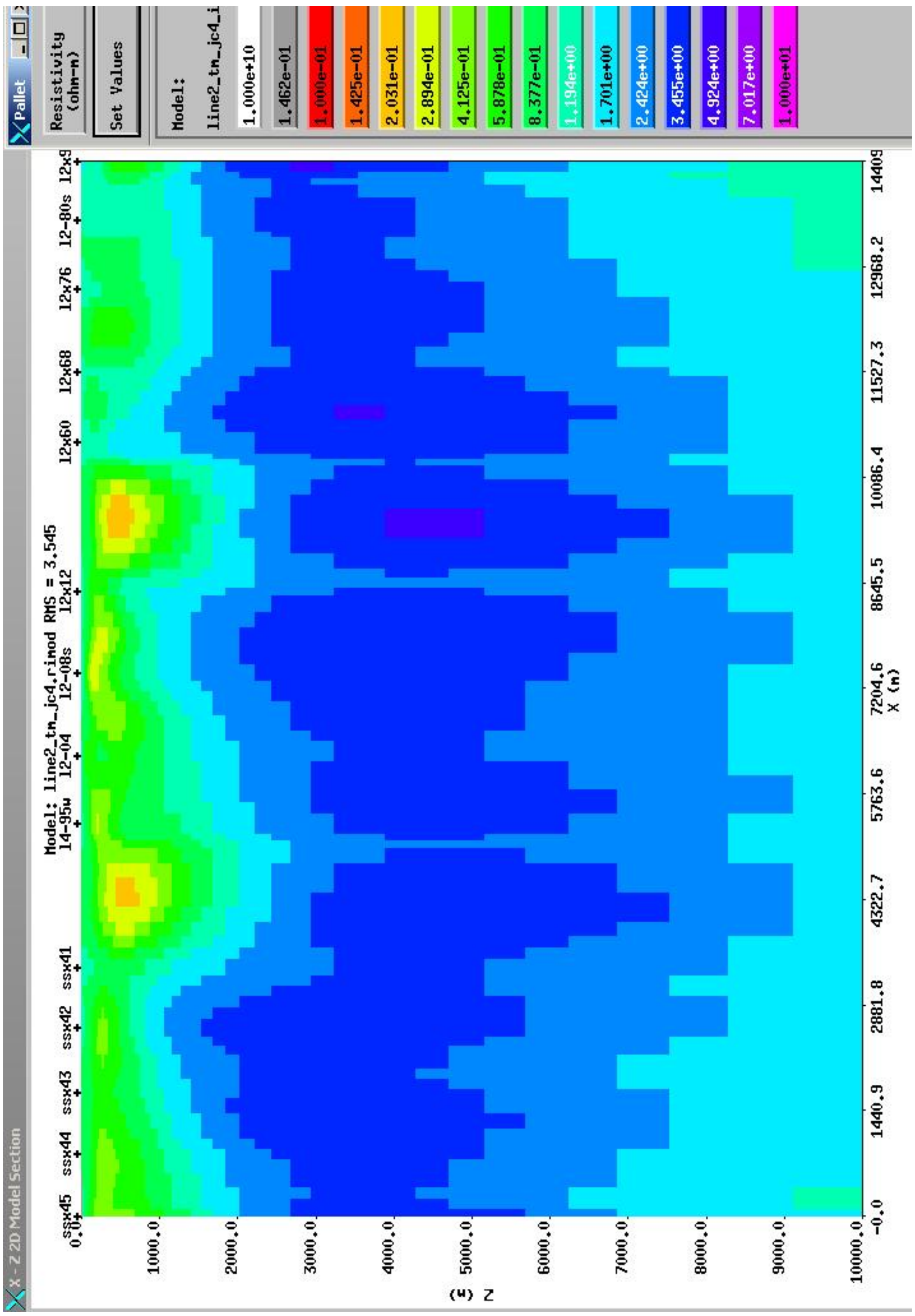

Figure 23: The inverted 2D resistivity profile along Line 2. (Schlumberger)

Profile Line 3

Similar procedures as in Profile Lines 1 and 2 were performed for Line 3 with the inverted results shown in Figure 24.

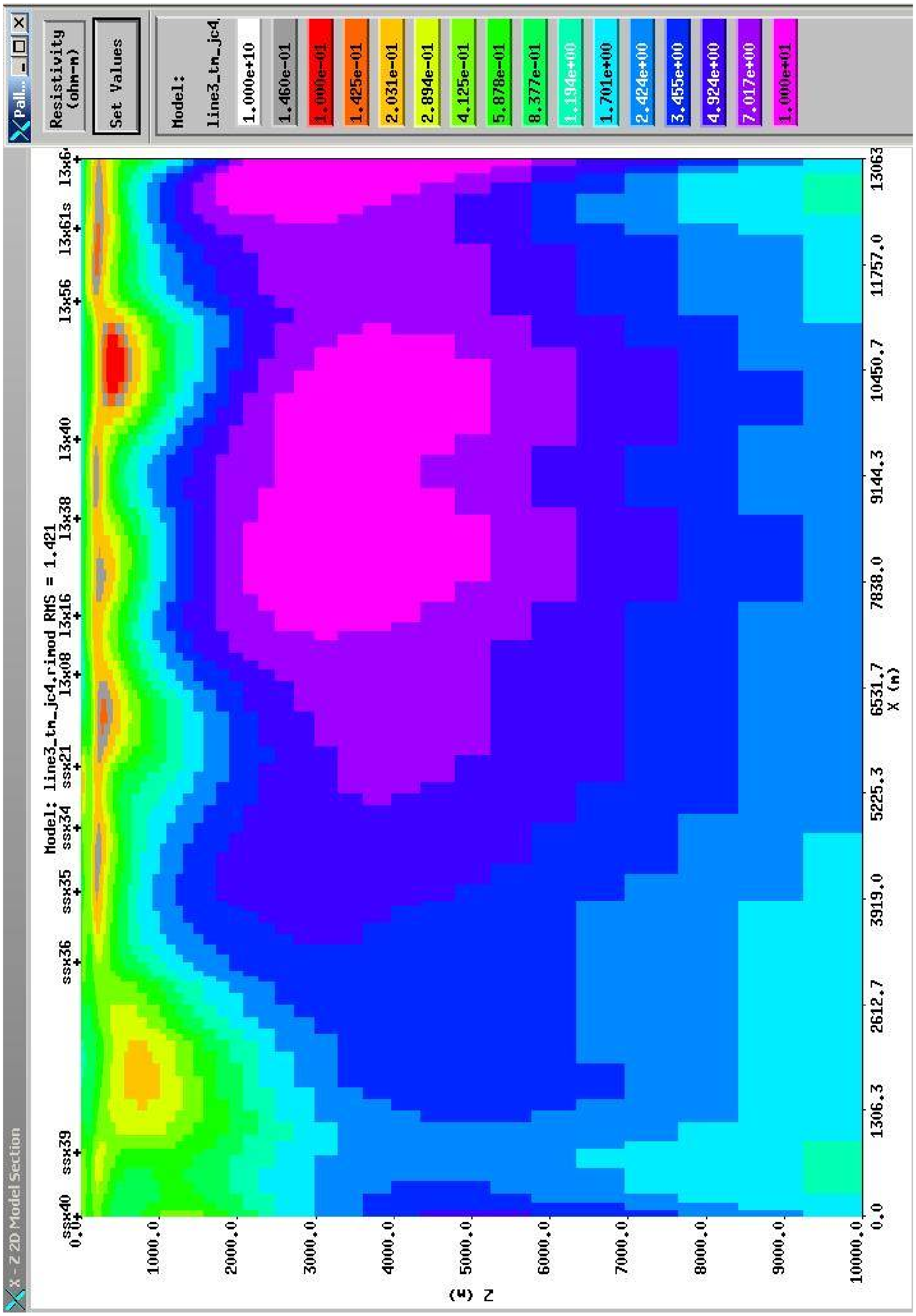

Figure 24: The inverted 2D resistivity profile along Line 3. (Schlumberger)

Profile Line 4

For Profile Line 4, the 2D assumption seemed to be valid. Therefore, TE and TM data were both used in the inversion. Other than that, similar procedures were adopted. In the inversions, two scenarios were tried. One was to use a uniform half space (1.0 Ohm-m) as an initial guess model, but the resistivity at each cell was free to be changed in the inversion process. The other was to fix the resistivity values outside of the core region. It seemed reasonable to include a prior knowledge about the high resistivity structure in the Chocolate Mountains and Superstition Mountain. It was found that by constraining the resistivity to be high and fixed inside these topographic zones, the inversion result was more appealing. Below is the inverted resistivity image with fixed zones (Figure 25).

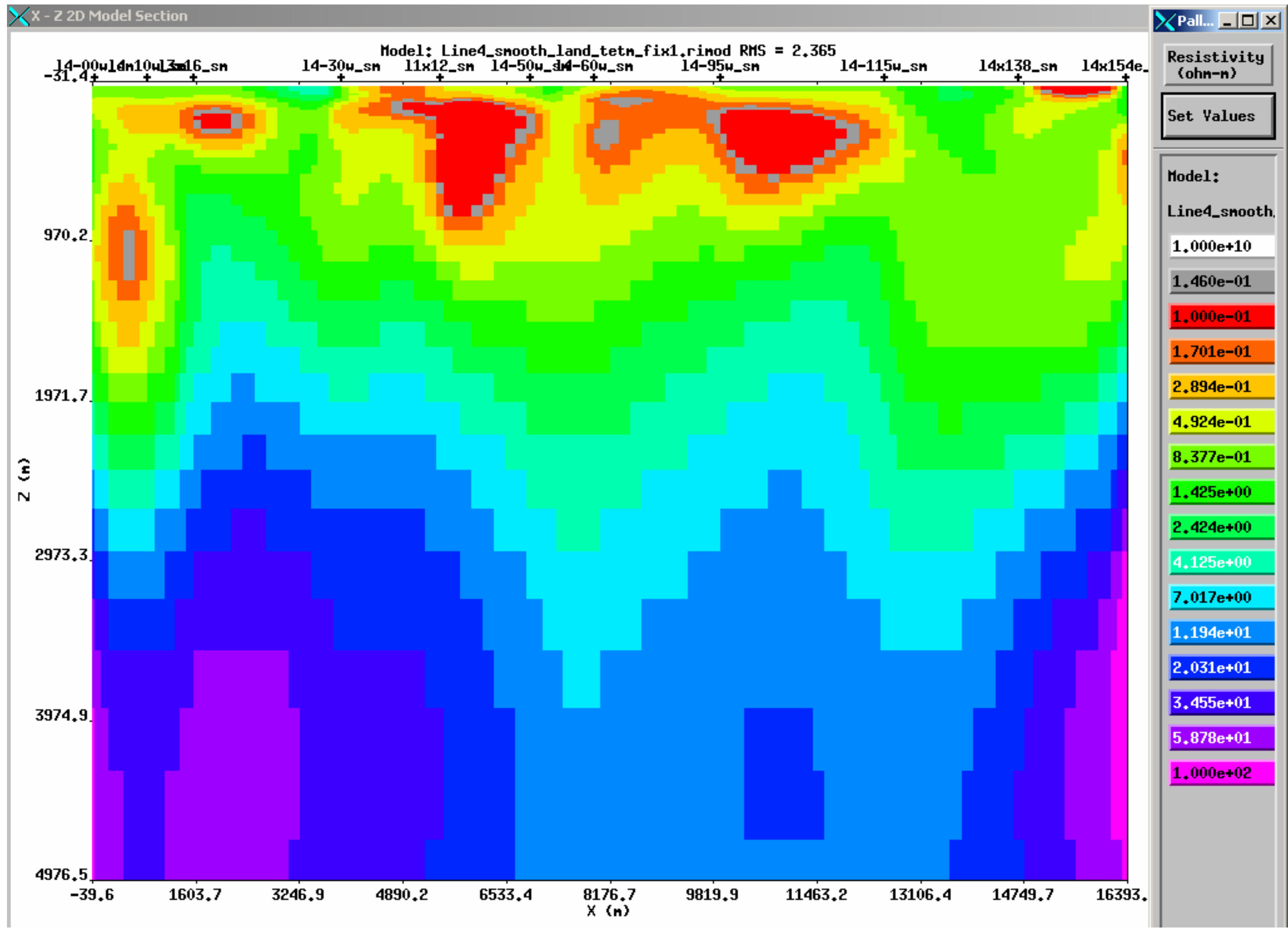

Figure 25: The inverted 2D resistivity profile along Line 4. (Schlumberger)

Geologic Integration

The inverted 2D resistivity profiles generally confirmed the understanding of the geologic structures. The upper three km can be divided into three layers:

1. a thin (about 300~600 m) surface cap of about 1 Ohm-m,

2. a very low resistive layer that is extremely conductive (0.2 ~ 1.0 Ohm-m), and

3. a relatively resistive basement (> 1.0 Ohm-m).

Geo-electrically, the first thin layer could be correlated with the sediments in the trough. The extremely conductive second layer may be due to the supersaline thermal fluids, and the third layer was believed to be the basement rock, which is the source of the geothermal fields.

Schlumberger met with CalEnergy representatives, Dennis Kaspereit and Brian Berard on April 11, 2006. The interpretations along the four profile lines were generally consistent with the main reservoir properties. The reservoir is the hot fluid contained in the high porosity sand and siltstones located beneath the low permeability altered cap rock. The reservoir is considered to be the subsurface volume with temperatures above 500F. The combination of high temperature, high saline waters in the reservoir and high porosity can produce electrical contrasts of more than 10x higher conductivity in the reservoir compared to cold volumes outside of the reservoir. Along the profiles there appeared to be correlation of the reservoir with high conductivity zones. For example, the deepening of the low resistivity areas along Line 2 corresponded with the drilling results along Line 2 (Figure 26).

The deep conductivity anomaly located along Line 1 was consistent with the area of highest field temperatures observed in the reservoir. Dennis Kaspereit wondered if this zone could be identifying the source region for the upwelling fluids in the field area. Unfortunately, there were no MMT sites available directly over this anomaly because these sites had poor data quality due to an extended period of high winds that coincided with data acquisition. It is recommended that this area should have repeat acquisition to help constrain the interpretation.

A preliminary 3-D visualization using all four profiles was prepared (see Figure 27). Further refinement of the model should continue by inclusion of all electrical well log information in the model.

The project has demonstrated that the electrical information obtained using MT is important for understanding the reservoir since the high temperature zones have a good high electrical conductivity response. The results obtained by this survey are consistent with previous surveys and previous well drilling information. The addition of the MMT technique has extended the size of the reservoir underneath the Salton Sea and has demonstrated the viability of MMT.

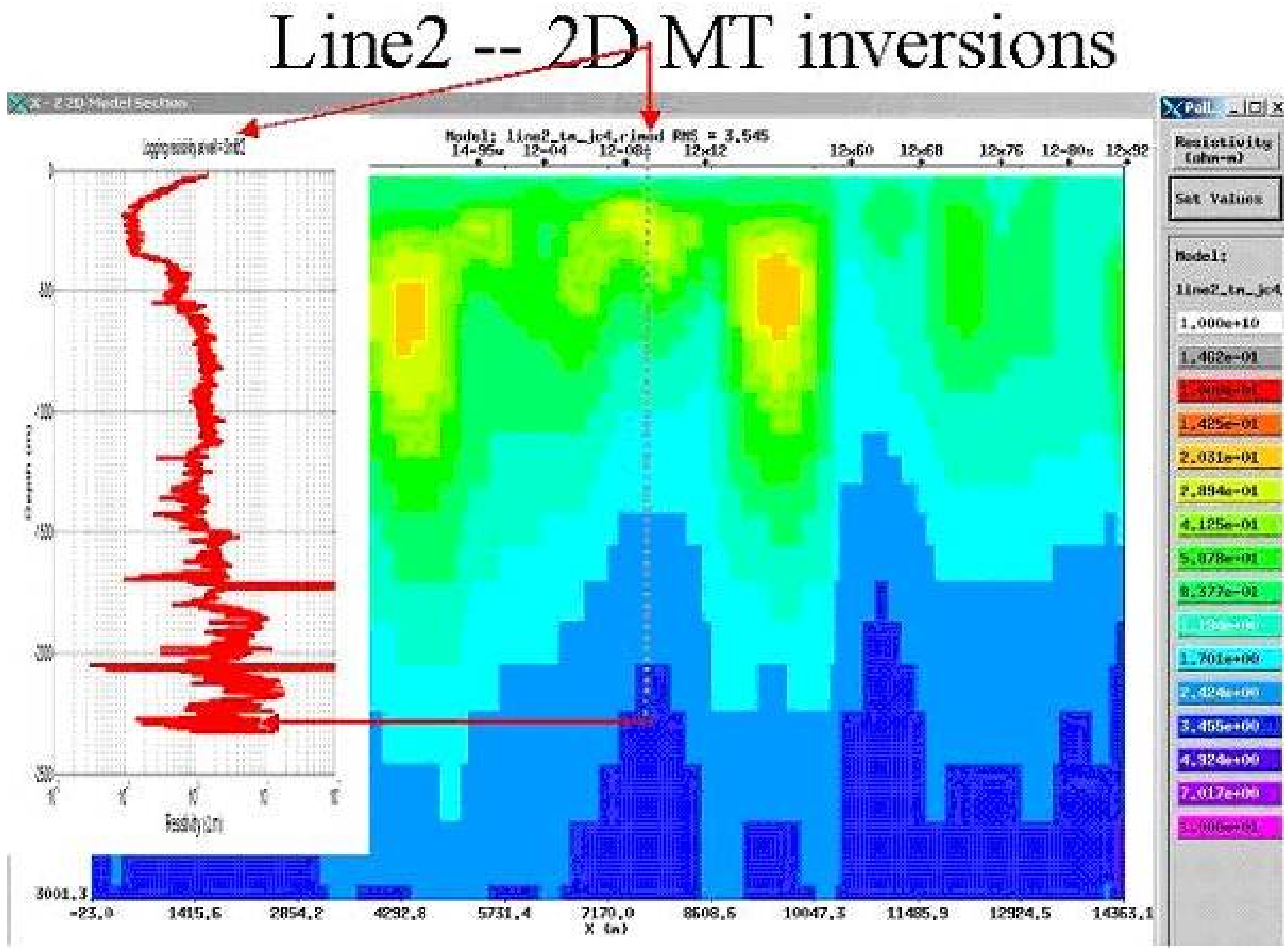

Figure 26: Tie up logs with one of the inversion profiles. (Schlumberger)

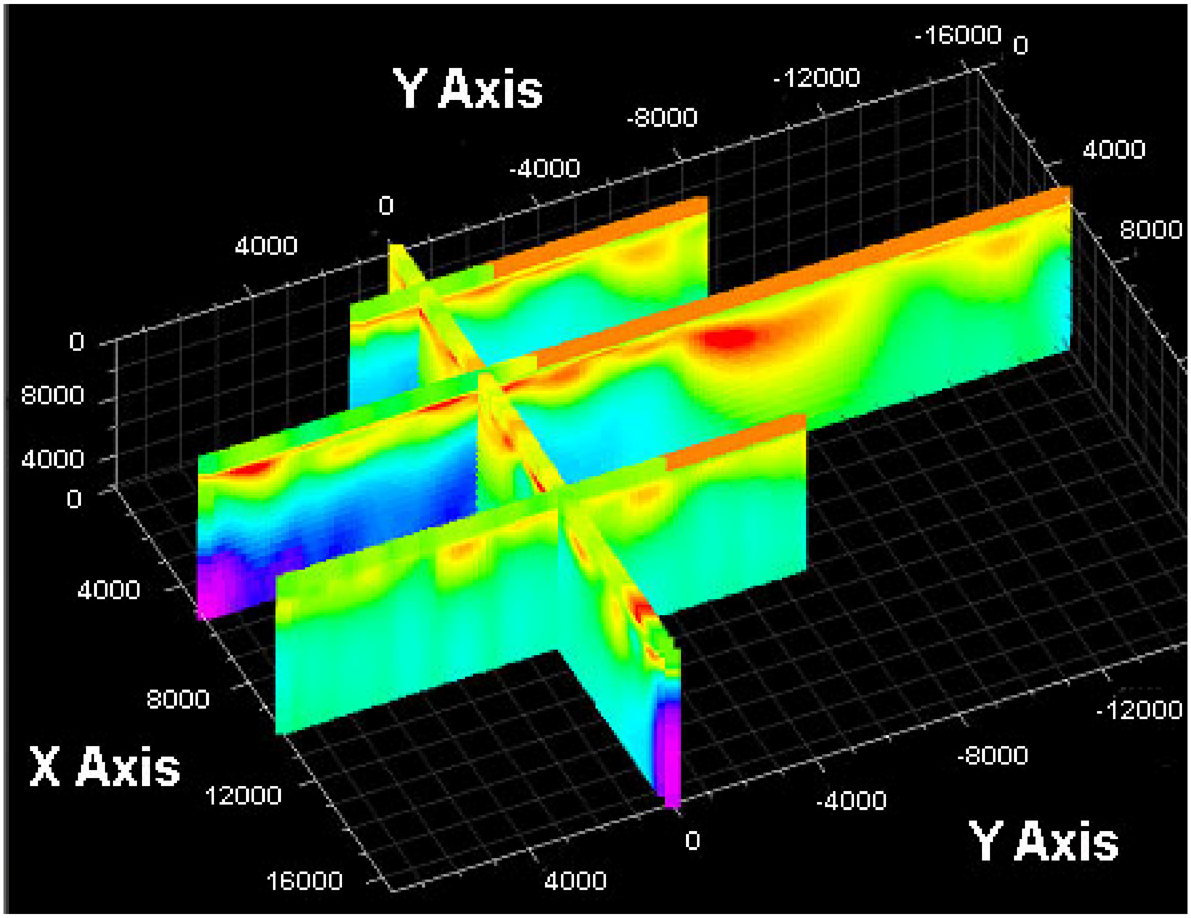

Figure 27: Three dimensional visualization of the subsurface electrical resistivity distribution four survey profile lines. (Schlumberger)

4 Conclusions and Recommendations

4.1 Conclusions

The PIER Program's goals for this project was to lower the risks and associated costs of developing a geothermal resource by improving exploration methods, improving understanding of basic geological conditions associated with hydrothermal systems, and enhancing reservoir management. The overall economic goal of this project was to develop and test a commercially viable exploration and monitoring technology for the geothermal industry. This project successfully demonstrated the technical achievements of this new integrated land-based and MMT project. This technology provides geothermal developers a new technique to better evaluate potential reservoir areas in a marine environment. In turn, this will enable effective exploration in new areas, develop and produce geothermal fields more efficiently, drill fewer dry holes and reduce the cost of electricity generation.

The first objective to plan and carry out a MT survey to determine the location of the boundaries of the Salton Sea Reservoir where it extends under the Salton Sea; and the second objective to demonstrate how MMT surveys can be extended to water covered areas for geothermal exploration were successfully carried out by demonstrating the first ever combined land/MMT survey which delineated the geothermal reservoir extending beneath the Salton Sea, in addition, it provided valuable structural geophyisical data of the area, especially in a shallow marine environment. Through this technology the unknown geothermal field boundaries and internal structure were mapped to more than ten kilometers past the known field boundaries.

This project partially achieved the technology transfer objective of providing to the geothermal industry the integrated results from the land-based and marine surveys, shallow geothermal gradient surveys, gravity and magnetic surveys by presenting the project results at the 2006 Geothermal Resources Council Annual meeting in San Diego, CA. The final objective of establishing a cost structure for providing commercial MT surveys to the geothermal industry was not achieved.

In the initial technical objectives outlined in the proposal, the purpose of this project was defined to engineer new MT instrumentation, design a full field coverage onshore/offshore MT experiment, conduct a field survey and interpret the results. This project was successful in meeting all of these objectives and in so doing has developed a new shallow water sea bed technology that can be used commercially worldwide. The results indicated that the geothermal reservoir has a markedly different resistivity signature than the background formation. The high temperature and high salinity brines reduce the resistivity by more than a factor of 30 as compared to the background and thereby make geothermal reservoir relatively easy to delineate based on the resistivity signature.

4.2 Commercialization Potential

MT is a well established exploration technique that uses surface measurements to map the deep subsurface electrical structure of the earth. For this project, new shallow water marine measuring equipment and successfully applied the measurements to extend the technology to shallow and deep water sea covered areas has been developed. This project has introduced a new technique to mapping electrical structure under other areas, not only in the Salton Sea but for other marine covered areas such as under the California Lakes: Clear Lake, Lake Tahoe, Mona Lake, Surprise Lake, or in the Gulf of California spreading zone.

There are many water-covered geothermal areas located around the world, some of which are located on the ocean bottom such as offshore Japan, Indonesia, Kamchatka or along the Red Sea Rift. Mid-ocean rift zones, especially those associated with mid sea island chains such as Iceland, are excellent candidates to apply this technology also.

In addition to geothermal applications, the technology also has significant applications within the much larger petroleum market. Shallow offshore applications are, in fact, the largest area for new petroleum exploration worldwide and this project presents a new tool for the arsenal of the exploration geologist.

4.3 Recommendations

Based on the results of this project additional work in four areas is recommended. First, additional, higher-density MT data coverage within the Salton Sea Field and on the border areas would be beneficial. An additional 30 stations would improve coverage and help to better define interfield resistivity structure. This is especially true in helping define new drilling targets.

Second, it would be useful to employ a 3D model and inversion code to interpret these data. This analysis would provide a much improved model as it would account for the basin structure as well as the field structure.

Third, it would be useful to incorporate these data with existing well data and seismic data to construct a full field geological model. This model would be invaluable in planning a field expansion, in conducting monitoring measurements during the field expansions and as a guide for other geothermal fields

Finally, create a permanent network of MT stations to be occupied during the next few years for field monitoring during the development and production phases. The hydrologic changes due to the production and injection of large volumes of brine and the removal of produced silica scale will result in significant subsurface changes that need to be monitored at a regular interval, and now is the time to start these activities.

4.4 Benefits to California

California has long been a leader in technology development; it is the nation's capitol for new ideas, now there is another one. This new technology is useful for geothermal field development within and outside the state. The technology is also has petroleum and environmental applications which have a continued and growing presence in California.

To interpret the data from this research, hardware and software is being developed by a California based technology center for continued commercial use. This process provides a number of good quality high-technology jobs to the state.

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Glossary

A/D	Analog to Digital
CEQA	California Environmental Quality Act
EDI	Electronic Data Interchange
em	Electromagnetic
FFT	Fast Fourier Transform
GEM	Geophysical Earth Model
HF	High Frequency
LLMMT_XP	Data Reduction Software for MT
MMT	Marine Magnetotellurics
MT	Magnetotelluric
nT	nanoTesla
s	Second
TE	Transverse Electric
TM	Transverse Magnetic
UTM	Universal Transverse Mercator

APPENDIX A: Estimated budget for work plan

Summary Project Budget Name of organization; Electromagnetic Instruments, Inc.		CEC Reimbursable Costs	Match Funds from Prime & Subs	Total Task Costs	CEC Percentage of Task Costs
1.0	**Project Start-Up Tasks**				
	1.1 Kickoff Meeting 1.2 Document Matching Funds 1.3 Identify Required Permits 1.4 Obtain Required Permits	1,778	1,778	3,555	50.0%
2.0	**Technical Tasks**				
	2.1 Survey Design and Test Survey				
	2.1.1 Identify the Geologic and the Geophysical Objectives	18,419	16,847	35,265	52.2%
	2.1.2 Test Survey	84,628	78,209	162,838	52.0%
	2.2.1 Marine Survey	143,358	133,338	276,696	51.8%
	2.2.2 Land Survey	75,092	40,184	115,276	65.1%
	2.2.3 Mid Term Project Review	2,398	0	2,398	100.0%
	2.3.1 Data Processing to Produce MT parameters	22,154	37,615	59,769	37.1%
	2.3.2 Data Interpretation to Produce Final Resistivity Sections	10,780	43,269	54,048	19.9%
	2.3.3 Geologic Integration	20,204	22,693	42,898	47.1%
	Technical Tasks Subtotals	377,032	372,155	749,187	50.3%
3.0	**Reporting Activities**				
	3.1 Quarterly Progress Reports and Task Reports	4,444	10,370	14,815	30.0%
	3.2 Final Report	5,333	5,333	10,666	50.0%
	3.3 Final Meeting	593	593	1,185	50.0%
	Reporting Activities Subtotals	10,370	16,296	26,666	38.9%

Project				CEC % of Total Cost
Totals	389,180	390,229	779,409	49.9%

APPENDIX B: Summary Category Budget

STATE OF CALIFORNIA
SUMMARY CATEGORY BUDGET

CALIFORNIA ENERGY COMMISSI

GEO-02-005

Recipient: Schlumberger Technology Corp, EMI Technology Center

Project Title: Geothermal Exploration Under The Salton Sea

Budget Category Item	*CEC Share*	*Match Share*	*Total Budget*
Personal Services:			
Personnel Direct Labor	125,853	101,184	227,037
Fringe Benefits	61,417	49,378	110,795
Total Personal Services	**187,270**	**150,562**	**337,832**
Operating Expenses:			
Travel	0	32,400	32,400
Equipment	0	0	0
Supplies	4,000	0	4,000
Contractual (Sub-Contracts)	2,000	26,500	28,500
Other	103,825	88,425	192,250
Total Operating Expenses	**109,825**	**147,325**	**257,150**
Indirect:			
Indirect Overhead	14,855	14,894	29,749
G&A Overhead	77,244	77,451	154,695
Total Overhead	**92,099**	**92,345**	**184,444**
TOTAL BUDGET	**389,194**	**390,232**	**779,426**

APPENDIX C: List of Site Owners

Profile Line 1 - 5 Km E

	Test	**(Sec) T/R**	**Property Owner**	**Contact Person**
	Survey			
150N	**5**	(32) 10/12	USA Salton Sea NWR	Sylvia R. Pelizza, Project Leader
134N	Site 1	(32) 10/12	USA Salton Sea NWR	Sonny Bono Salton Sea NWRC
118N		(4) 11/12	USA Salton Sea NWR	906 W. Sinclair Road
92N		(10) 11/12	USA Salton Sea NWR	Calipatria, CA 92233
76N		(14) 11/12	USA Salton Sea NWR	760-348-5278
60N		(14) 11/12	USA Salton Sea NWR	760-348-7245 FAX
44N	Site 2	(24) 11/12	USA Salton Sea NWR	Sylvia_Pelizza@r1.fws.gov
36N		(24) 11/12	USA Salton Sea NWR	
28N		(30) 11/13	Imperial Irrigation District	Jim Kelley, jpkelley@iid.com
20N		(30) 11/13	Imperial Irrigation District	Supervisor, Real Estate
12N		(30) 11/13	Imperial Irrigation District	Imperial Irrigation District
8N		(32) 11/13	Imperial Irrigation District	333 E. Barioni Boulevard
4N		(32) 11/13	Imperial Irrigation District	P.O. Box 937
0N or L4-50E	Site 7	(32) 11/13	Imperial Irrigation District	Imperial CA 92251
4S		(32) 11/13	Imperial Irrigation District	FAX: 760-339-9127
8S		(32) 11/13	Burdick, B&V (TRS) et al 40	Burdick Beth Burdick, 6949 S. Eudora St,
12S		(32) 11/13	Burdick, B&V (TRS) et al 40	Centennial CO 90122-2356
16S		(4) 12/13	Kudu, Inc.	Richard Elmore Tel: 760-344-4250
20S		(4) 12/13	Kudu, Inc.	696 N. 8th St., Brawley, CA 92227
24S	Site 8	(4) 12/13	Kudu, Inc.	Harthill Acres pirate@brawleyonline.com
28S		(4) 12/13	Union Oil	Jack Marshall 714-577-1691, jamarsha@unocal.com
				Union Oil of California Attn: Property Tax
				376 S. Valencia Ave., Brea CA 92822
32S		(4) 12/13	Elmore, J.J.	Richard Elmore Tel: 760-344-4250
36S		(10) 12/13	Morgan, M&D	Mike Morgan Tel: 760-344-5253
				3949 Austin Rd., Brawley, CA 92227
44S		(10) 12/13	Morgan, M&D	Harthill Acres pirate@brawleyonline.com
				Harthill Acres pirate@brawleyonline.com
52S		(10) 12/13	Ann Kelley Elmore Ltd. Partnership	Richard Elmore Tel: 760-344-4250
60S	Site 9	(14) 12/13	Elmore, J.J. (TRS)	Richard Elmore Tel: 760-344-4250
76S		(14) 12/13	Johnson, P.E., (TR) et al.	
92S		24) 12/13	Caston, A.H. (TR)	Elsie J. Caston Tel: 619-267-2176
				2931 Plaza Miguel, Bonita CA 91902

Alternate sites, Profile Line 1

8S East		(33) 11/13	Imperial Magma	Vince Signoritti
				c/o Mid American Energy Corp. Tax Dept.
12S East		(33) 11/13	Imperial Magma	PO Box 657, Des Moines, IA 50303
16S W		(5) 12/13	Magma Land Co.	Vince Signoritti
16S E		(4) 12/13	Imperial Magma	PO Box 657, Des Moines, IA 50303
20S W		(5) 12/13	Magma Land Co.	
20S E		(4) 12/13	Harthill Acres	Mike Morgan Tel: 760-344-5253
24S	Site 8	(4) 12/13	Union Oil	Jack Marshall jamarsha@unocal.com
24S	Site 8	(4) 12/13	Harthill Acres	Harthill Acres pirate@brawleyonline.com
28S E		(4) 12/13	Elmore, J.J	Richard Elmore Tel: 760-344-4250
76S E		(13) 12/13	Caston, A.H. (TR)	Elsie J. Caston Tel: 619-267-2176
76S E		(13) 12/13	Brandt, W.&S.	Mark Brandt Tel: 760-344-2707
92S		(24) 12/13	Delta Plantation, Inc.	

Profile Line 2 - 9.4 Km E

		(Sec) T/R	Property Owner	Contact Person
52N		(8) 11/13	USA Salton Sea NWR	
44N		(8) 11/13	USA Salton Sea NWR	
36N		(8) 11/13	USA Salton Sea NWR	
28N		(16) 11/13	Imperial Irrigation District	Jim Kelley, Supr, jpkelley@iid.com
20N		(16) 11/13	Imperial Irrigation District	Real Estate
4N		(22) 11/13	Imperial Irrigation District	Imperial Irrigation District
0 L4-94E		(22) 11/13	Imperial Irrigation District	333 E. Barioni Boulevard
4S		(22) 11/13	Imperial Irrigation District	P.O. Box 937
8S		(22) 11/13	Imperial Irrigation District	Imperial CA 92251
12S		(22) 11/13	Imperial Irrigation District	FAX: 760-339-9127
16S		(26) 11/13	Imperial Irrigation District	Jim Kelley Tel: 760-339-9239
28S		(26) 11/13	Smith, J&B	R. Smith Tel: 760-344-1682
32S		(26) 11/13	Smith, J&B	1593 E. Gonder Rd., Brawley, CA 92227
36S		(25,26) 11/13	Smith, J&B	R. Smith Tel: 760-344-1682
40S		(36) 11/13	Imperial Irrigation District (if in river bottom)	Jim Kelley Tel: 760-339-9239
44S		(36) 11/13	Imperial Irrigation District (if in river bottom)	Jim Kelley Tel: 760-339-9239
52S		(36) 11/13	Imperial Irrigation District	Jim Kelley Tel: 760-339-9239
60S		(6) 12/14	Brandt, W.&S.	Mark Brandt Tel: 760-344-2707
68S		(6) 12/14	Western Farms, L.P.	See above
76S		(6) 12/14	City of Calipatria Annex	

92S		(8) 12/14	Western Farms	40-004 Cook St. Palm Desert, CA 92211

Alternate sites, Line 2

12S		(22) 11/13	State of California	James Chakarun Tel: 760-485-8085
				jchakaru@dfg.ca.gov
16S		(26) 11/13	State of California	8700 Davis Rd., Niland, CA 92257
16S sw alt.			Imperial Magma	Vince Signoretti
28S right alt.		(25,26) 11/13	Imperial Magma	c/o Mid American Energy Corp. Tax Dept.
32S right alt		(25,26) 11/13	Imperial Magma	PO Box 657, Des Moines, IA 50303
36S right alt.		(25,26) 11/13	Magma Power Co.	
36S right alt.		(36) 11/13	Imperial Irrigation District	Jim Kelley Tel: 760-339-9239
40S		(36) 11/13	Reynolds, R.J.	Joyce Reynolds Tel: 760-352-2457
				1915 S. 9th St., El Centro, CA 92243
40S right alt.		(36) 11/13	Wiest, J.W.	Bill Wiest Tel: 760-344-0687
				388 South Russell Rd, Brawley, CA 92227
44S		(36) 11/13	Reynolds, R.J.	Joyce Reynolds Tel: 760-352-2457
				1915 S. 9th St., El Centro, CA 92243
44S right alt.		(36) 11/13	Wiest, J.W.	Bill Wiest Tel: 760-344-0687
52S right alt.		(36) 11/13	Brandt, M. et al.	Mark Brandt Tel: 760-344-2707
52S alt.		(36) 11/13	Brandt, W.&S.	Mark Brandt Tel: 760-344-2707
60S		(6) 12/14	Western Farms, LP	Frederick Noble, Jr. Tel: 760-340-0098
				40-004 Cook St. Palm Desert, CA 92211
68S		(6) 12/14	City of Calipatria Annex	
76S		(6) 12/14	Wiest Ranches Inc. B	Bill Wiest Tel: 760-344-0687
76S		(6) 12/14	Wiest, J.&M.	388 South Russell Rd, Brawley, CA 92227
76S		(6) 12/14	Western Farms, LP	Frederick Noble, Jr. Tel: 760-340-0098
92S		(8) 12/14	Malone, A.L.	A. Malone Tel: 760-946-2849, or 384-1623
				Apple Valley, Ridgecrest
92S		(8) 12/14	Maraccini Inc.	Maraccini Center Tel: 760-344-4360

				1321 E. Main St., Brawley, CA 92227

Profile Line 3 - 1 km E

		(Sec) T/R	Property Owner	Contact Person
56N		(27) 11/12	USA Salton Sea NWR	Sylvia R. Pelizza, Project Leader
48N		(34) 11/12	USA Salton Sea NWR	Sonny Bono Salton Sea NWRC
40N		(34) 11/12	USA Salton Sea NWR	906 W. Sinclair Road
32N		(35) 11/12	Imperial Irrigation District	Jim Kelley Tel: 760-339-9239
24N		(2) 12/12	USA Salton Sea NWR	
16N		(1) 12/12	Imperial Irrigation District	Jim Kelley, Supervisor jpkelley@iid.com
8N		(1) 12/12	Imperial Irrigation District	Real Estate
0N L4-10E	Site 3	(12) 12/12	Imperial Irrigation District	Imperial Irrigation District
8S		(7) 12/13	Imperial Irrigation District	333 E. Barioni Boulevard
16S		(7) 12/13	Elmore, SH et al.	P.O. Box 937
24S		(18) 12/13	Sage et al.	
32S		(17) 12/13	Jordan, Hetty J. Elmore	H. Jordan Tel: 760-956-4773
40S		(17) 12/13	Jordan, H.J.	1280 E. Main St., Brawley, CA 92227
			Sage et al.	
			Brandt, W.&S.	Mark Brandt Tel: 760-344-2707
48S		(20) 12/13	Brandt, W.&S.	PO Box 118, Brawley, CA 92227
56S		(21) 12/13	Elmore, J.J. Et al.	Richard Elmore Tel: 760-344-4250

Alternate sites, Profile Line 3

16S left alt.		(7) 12/13	Imperial Irrigation District	Jim Kelley Tel: 760-339-9239
24S up alt.		(7) 12/13	Elmore, SH et al.	Richard Elmore Tel: 760-344-4250
24S right alt.		(17) 12/13	Russell Bros. Ranches, Inc.	Russell Bros. Tel: 760-629-3060
32S up alt.		(17) 12/13	Russell Bros. Ranches, Inc.	220 W. Main St. B, Brawley, CA 92227
48S		(20) 12/13	Elmore, J.J. Et al.	Richard Elmore Tel: 760-344-4250
64S		(21) 12/13	Morgan, M.&D.	Mike Morgan Tel: 760-344-5253

Profile Line 4 - Baseline

	Test	(Sec) T/R	Property Owner	Contact Person
46 W		(22) 12/12	IID, all except NW corner, close to USA	Jim Kelley, Tel: 760-339-9239
30 W		(14) 12/12	Imperial Irrigation District	Jim Kelley, Tel: 760-339-9239
			USA Salton Sea NWR	SBNWR - Sylvia Pelizza
14 W		(14) 12/12	Imperial Irrigation District	Jim Kelley, Supr., jpkelley@iid.com
2 E		(12) 12/12	Imperial Irrigation District	Real Estate
10 E	Site 3	(12) 12/12	Imperial Irrigation District	Imperial Irrigation District
18 E		(6) 12/13	Imperial Irrigation District	333 E. Barioni Boulevard
22 E		(6) 12/13	Imperial Irrigation District	P.O. Box 937
26 E		(6) 12/13	Imperial Irrigation District	Imperial CA 92251
30 E		(6) 12/13	Imperial Irrigation District	FAX: 760-339-9127
34 E		(6) 12/13	Imperial Irrigation District	
38 E	Site 4	(31) 11/13	Imperial Irrigation District	
42 E		(32) 11/13	Imperial Irrigation District	
46 E		(32) 11/13	Imperial Irrigation District	
50 E	Site 7	(32) 11/13	Imperial Irrigation District	
54 E		(32) 11/13	Imperial Irrigation District	
58 E		(32) 11/13	Imperial Irrigation District	
62 E		(29) 11/13	Imperial Irrigation District	
66 E	Site 5	(28) 11/13	Imperial Irrigation District	
70 E		(28) 11/13	Imperial Irrigation District	
74 E		(28) 11/13	Imperial Irrigation District	
78 E		(28) 11/13	Imperial Irrigation District	
82 E		(28) 11/13	Imperial Irrigation District	
86 E		(22) 11/13	Imperial Irrigation District	
90 E	Site 10	(22) 11/13	Imperial Irrigation District	
94 E		(22) 11/13	Imperial Irrigation District	
102 E		(22) 11/13	Imperial Irrigation District	
106 E		(15) 11/13	Imperial Irrigation District	
114 E	Site 6	(14) 11/13	Imperial Irrigation District	
122 E		(14) 11/13	Imperial Irrigation District	
138 E		(12) 11/13	128 separate 1.25 acre parcels	
			State of California	James Chakarun Tel: 760-485-8085
154 E		(6) 11/14	State of CA	8700 Davis Rd, Niland, CA 92257
170 E		(6) 11/14	Waddell, J& P (TRS)	
			Western Farms, LP	Frederick Noble, Jr., Tel: 760-340-0098
				c/o US Filter Farms GP Inc.

			Honkers Hunting Club	

APPENDIX D: Sample Cover Letter

August 22, 2003

Electromagnetic Instruments, Inc.
1301 South 46th Street
Bldg. 300, Richmond Field Station
University of California
Richmond, CA 94804
Tel: 510-232-7997
Fax: 510-232-7998

Richard Elmore
Kudu, Inc.
Tel: 760-344-4250

Dear Mr. Elmore,

EMI, Inc. will conduct a magnetotelluric survey for the California Energy Commission (Energy Commission) in and around the Salton Sea. This survey will use standard magnetotelluric sensors (buried electrodes, induction coils, and cables) to measure the natural electric and magnetic fields. The equipment will be deployed by burying the electrodes and magnetic sensors using a shovel in small trenches up to one foot beneath the surface. We bury the sensors so that they are not disturbed by wind or animal life during the recording period (~5 days). Afterwards, we will collect the equipment and restore the ground to its original state. The goal of this survey is to look for extensions of the geothermal field under the Salton Sea.

Our survey consists of two phases.

1) Preliminary test survey in which we will take 6 sites in the Salton Sea and four on land. This survey phase is planned for the window of Sept. 20 to Sept 30, 2003. We have identified two of the sites #6 and # 8 as being on your land.
2) Main survey phase is planned for November to December 2003. This phase will consist of recording an additional 72 sites of which approximately 44 are located in the Salton Sea. 11 further sites are on your land.

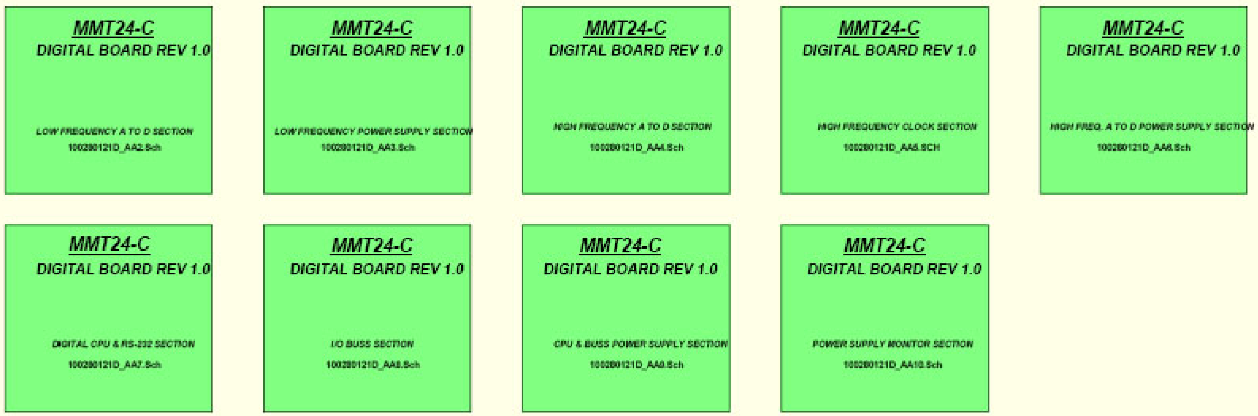
We have attached copies of our work statement proposal to as well as a map showing the proposed sites and an authorization letter. Please sign and return the authorization letter in the self addressed stamped envelope granting us permission to set up and install our recording equipment for the sites we have identified. Please contact us if you have any questions or concerns.

Sincerely,
Edward Nichols

APPENDIX E: Electronic Schematic Diagrams

NOTES:

MMT24-C DIGITAL BOARD REV 1.0



DESIGN CHANGES

1. REDUCED LOW FREQUENCY CHANNELS FROM 10 CHANNELS TO 8 CHANNELS.
2. ADDED HIGH FREQUENCY CHANNELS FROM 6 CHANNELS TO 8 CHANNELS.
3. ADD SOFTWARE CHANGE TO CONTROL THE SHUTDOWN OF HIGH FREQUENCY CHANNELS AS FOLLOWS: CHANNELS A, B, C, D, E, F, G, & H. "HFSHDN". CHANNELS E, F, G, & H "BUSS D8".
4. FOR HIGH FREQUENCY A TO D'S, ADD POWER SUPPLY "POWER-UP" DELAYS WITH ANALOG POWER SUPPLY TO COME-UP BEFORE THE DIGITAL SUPPLY.
5. ADDED "TURN-ON" DELAY OF CLOCK SIGNALS OF HIGH FREQUENCY A TO D'S CLOCK SIGNAL AFTER ALL POWER SUPPLIES ARE UP.
6. REASSIGN PIN FUCTION OF MOVED MHC-13 FROM GTX TO POWER UP THE 6V AND 9V POWER SUPPLIES WHILE "PLUG-IN".

REFERENCE DESIGNATORS USED FOR PAGE 2

Cx	Dx	Hx	Jx	Rx	TPx	Ux
C1A-C1H	Dx	Hx	J1	R1A-R1H	TP1A- TP1H	U1A-U1H
C2A-C2H			J6	R2A-R2H		U2A-U2H
C3A-C3H				R3A-R3H		
C4A-C4H				R4A-R4H		
				U5H, R6H		

REFERENCE DESIGNATORS USED FOR PAGE 3

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C40-C78	Dx	H7	J2-J4	R40-R53	TP14-TP18	U15-U18

REFERENCE DESIGNATORS USED FOR PAGE 4

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C90A-H	Dx	Hx	Jx	R80A-H	TP18A-H	U21A-H
C91A-H						
C92A-H						

REFERENCE DESIGNATORS USED FOR PAGE 5

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C100	Dx	G1	JJ5	R70-R74	TP22-TP28	U30-U38

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C110-C118	D1-D9	Hx	JJ1- JJ3	R80-R81	TP30-TP36	U40-U48
C119A,C,E,G				R82A,C,E,G		
C120A,C,E,G				R85A-H		
C125A-H				R86A-H		
C126A-H				R87-R115		
C127A-H						
C128A-H						
C149-C181						

REFERENCE DESIGNATORS USED FOR PAGE 7

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C182-C188	D10	BAT1	Jx	R120-R129	TP-X, TP-Y,	U50-U54
					TP- Z	

REFERENCE DESIGNATORS USED FOR PAGE 8

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Cx	Dx	Hx	J5	R130-132	TP-CSHF	U60-U67
				R133A-H	TP-HSCLK	U68A-H
					TP-SDIOH	
					TP-DSYNC	
				TP-37-38	TP-CSLF	
				TP-CSLF3	TP-SHDN	
				TP-HFSHDN	TP-PCLK	
				TP-SCKLF3	TP-SCK_LF	

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C190-C224	Dx	Hx	Jx	R134-R151	TPx	U80
C230A-H				R153A-H		

REFERENCE DESIGNATORS USED FOR PAGE 10

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C234-C261	D11-D13	Hx	P1, JP1-4	R160-R208	TP40-TP47	U70-U74

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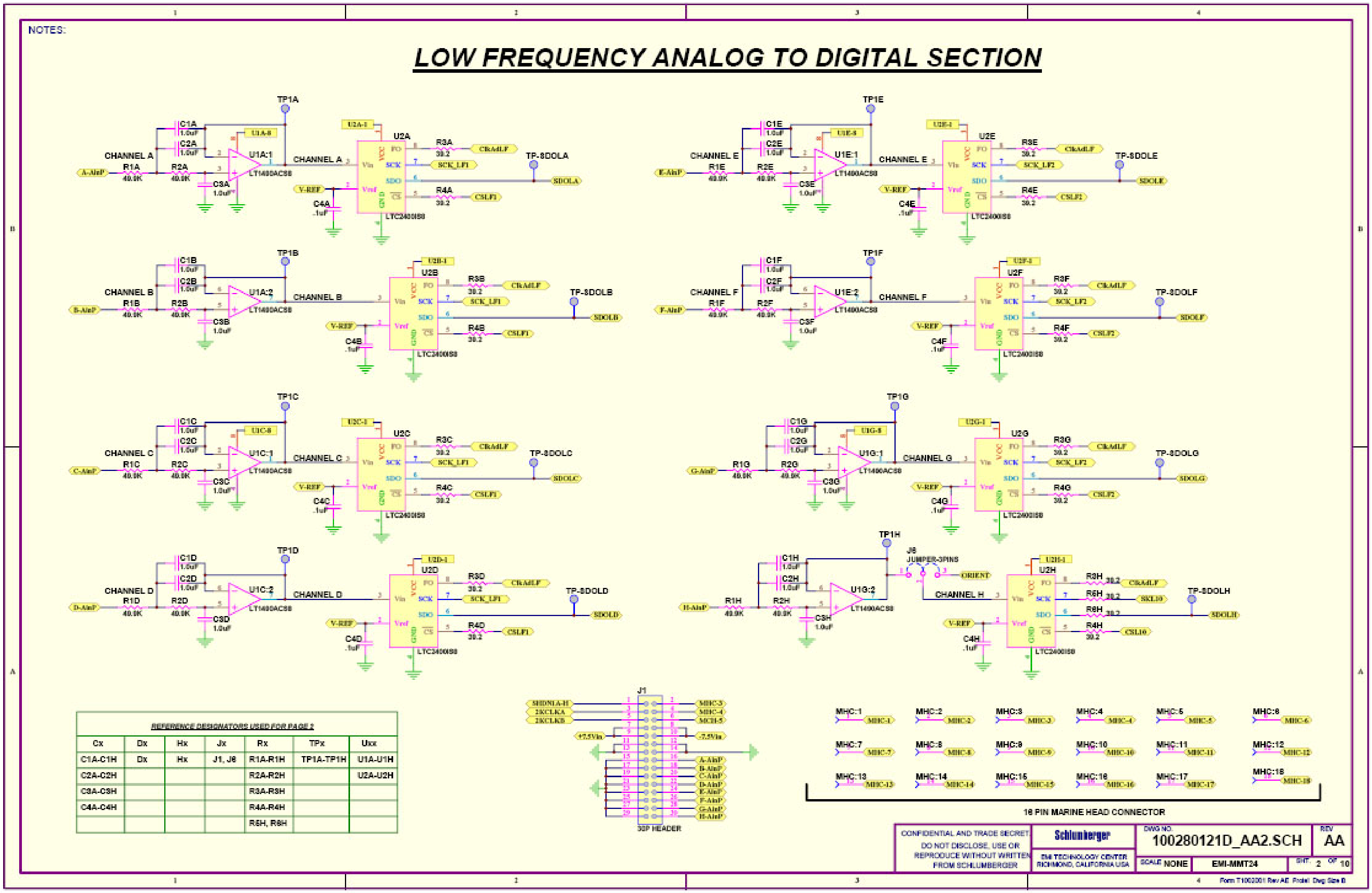
RICHMOND, CALIFORNIA USA

DWG NO. 100280121D_AA1.SCH			REV AA
SCALE NONE	EMI-MMT24	SHT. 1	OF 10

Form T1002001 Rev AE Protel Dwg Size B



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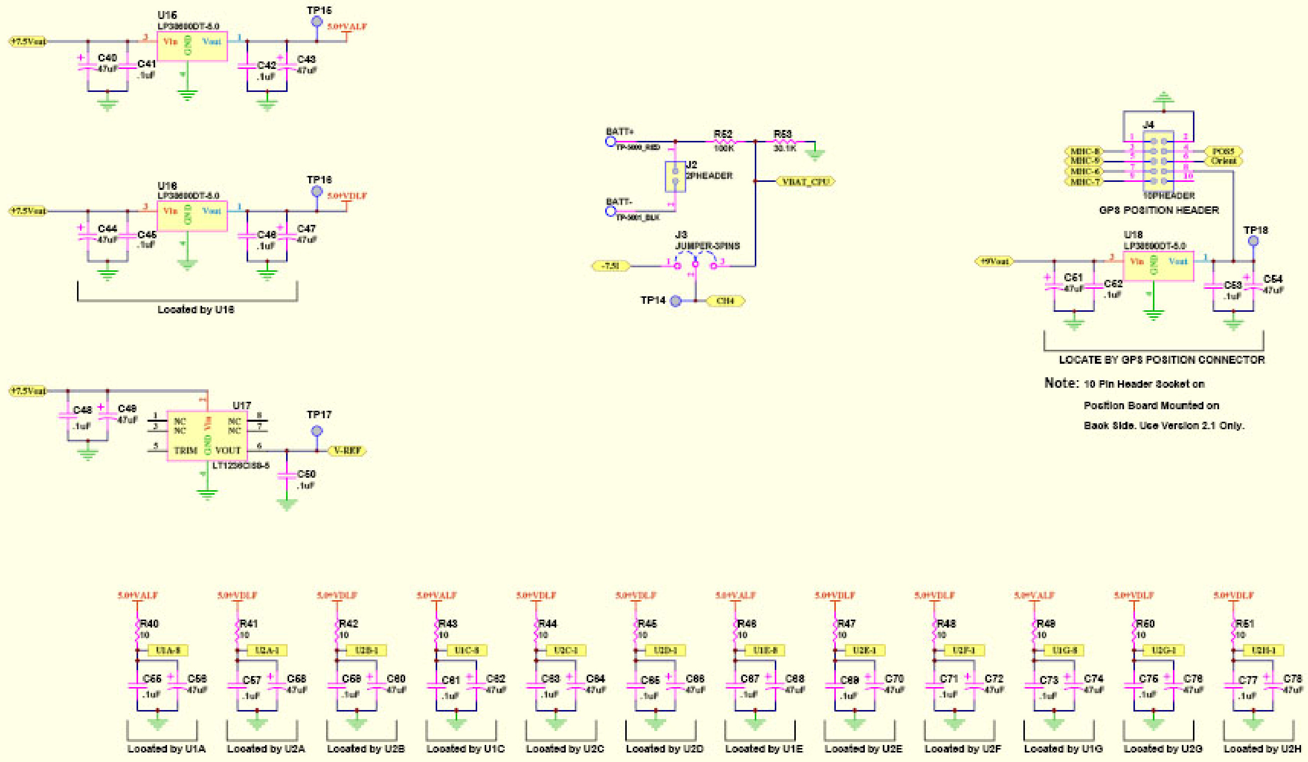
C3A-C3H				R3A-R3H		
C4A-C4H				R4A-R4H		
				R5H, R6H		

NOTES:

LOW FREQUENCY A TO D POWER SUPPLY SECTION



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C55-C78						

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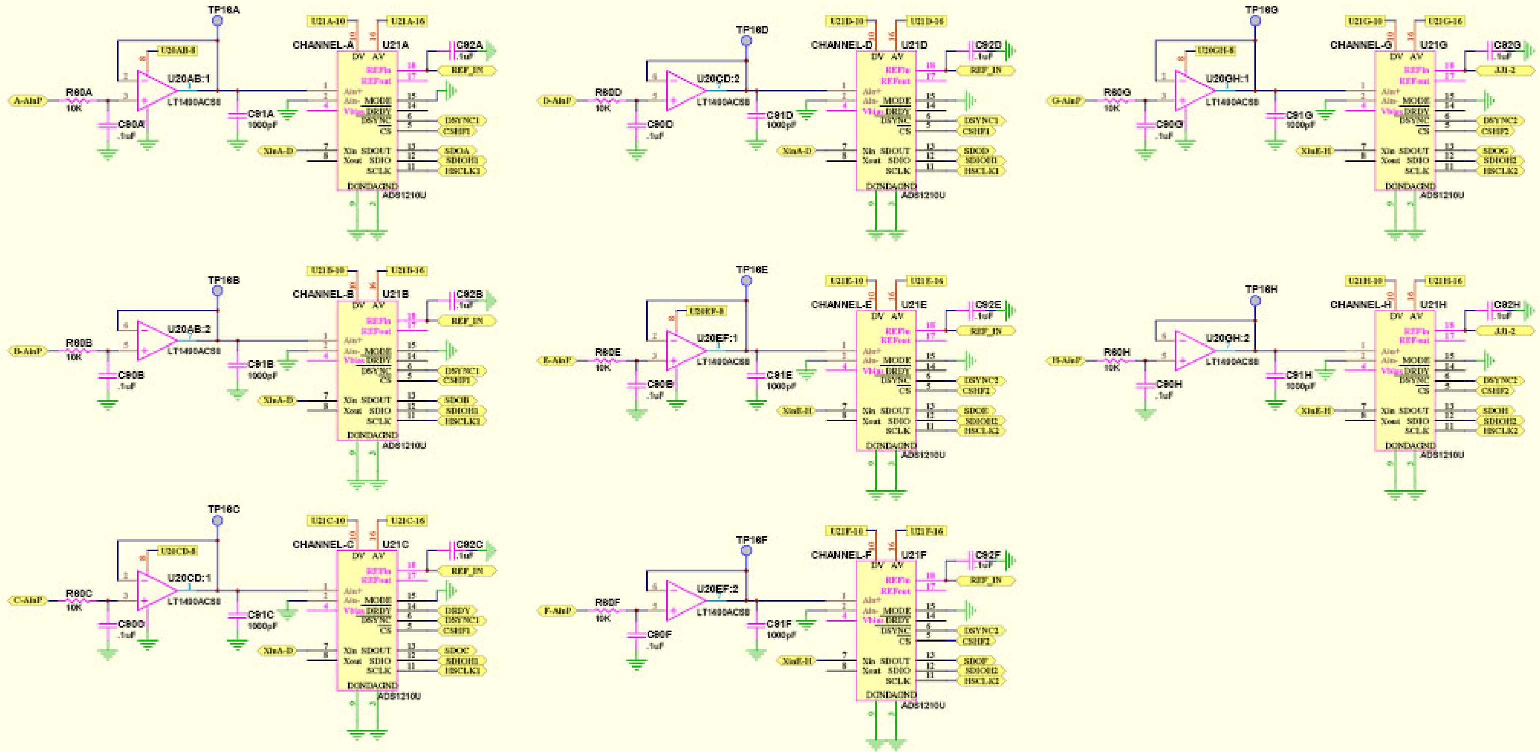
Form T1002001 Rev AE Protel Dwg Size B

NOTES:

HIGH FREQUENCY A TO D SECTION



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C81A-H						
C82A-H						

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REV AA

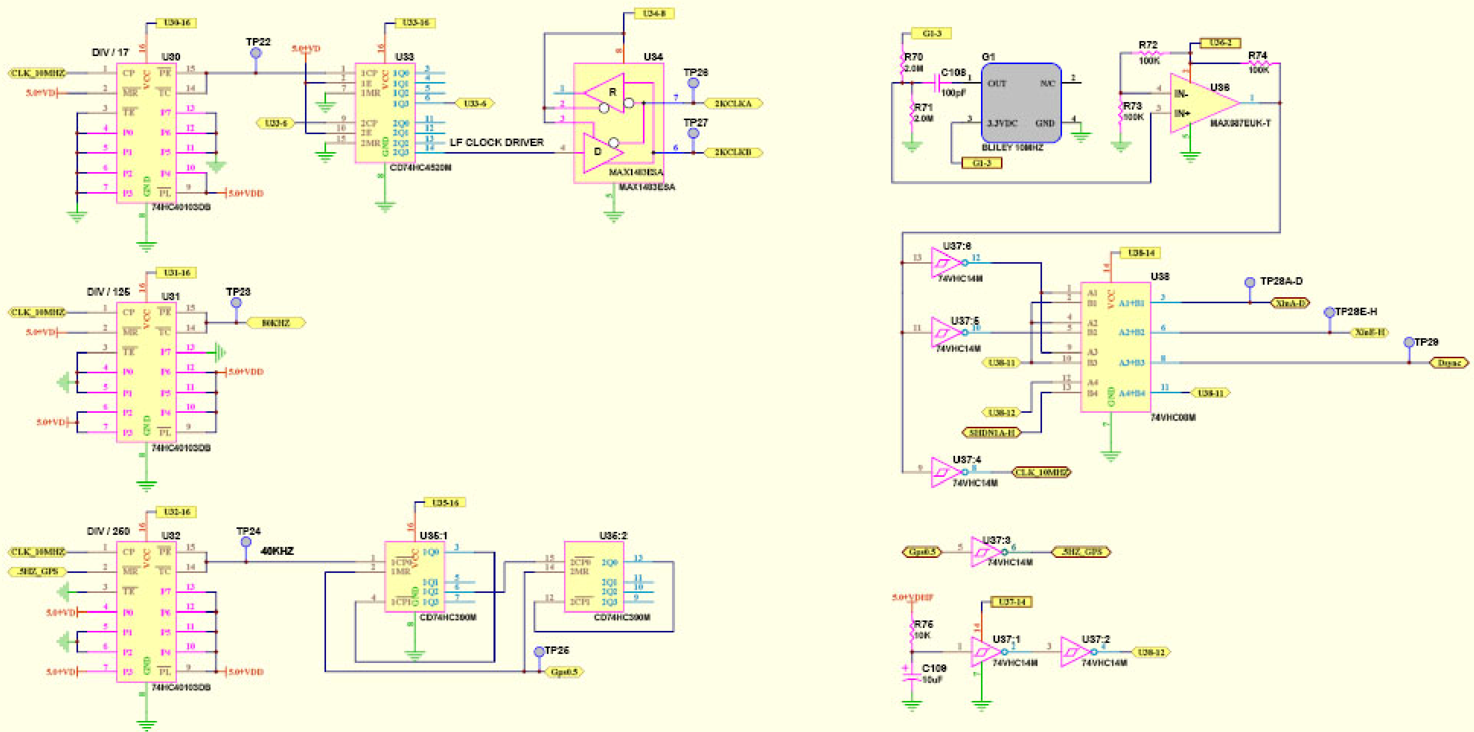
SCALE NONE

EMI-MMT24

SHT 4 OF 10

NOTES:

HIGH FREQUENCY CLOCK SECTION



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C108	Dx	G1	JJ6	R70-R74	TP22-TP29	U30-U38

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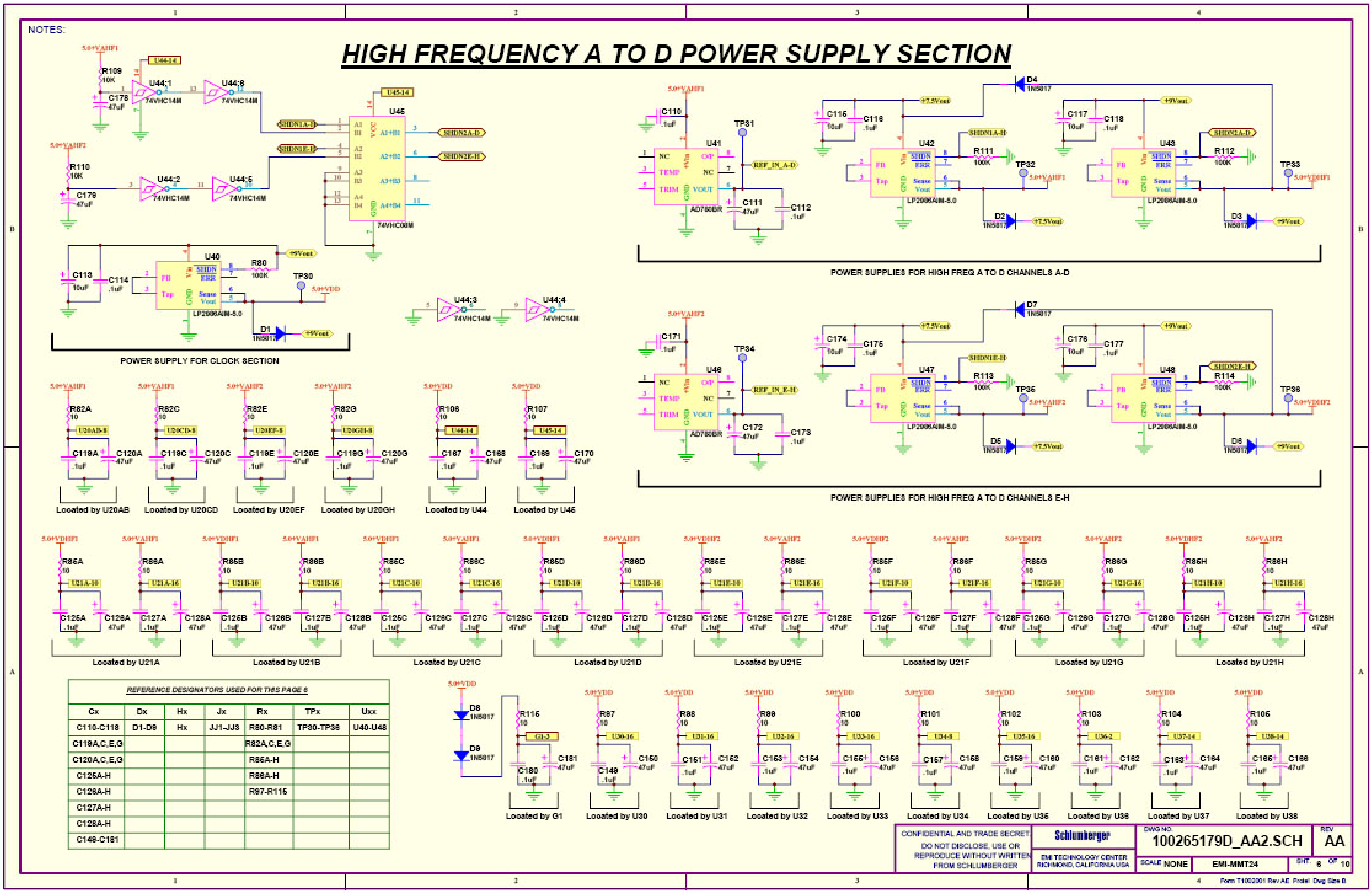
Form T1002001 Rev AE Protel Dwg Size B



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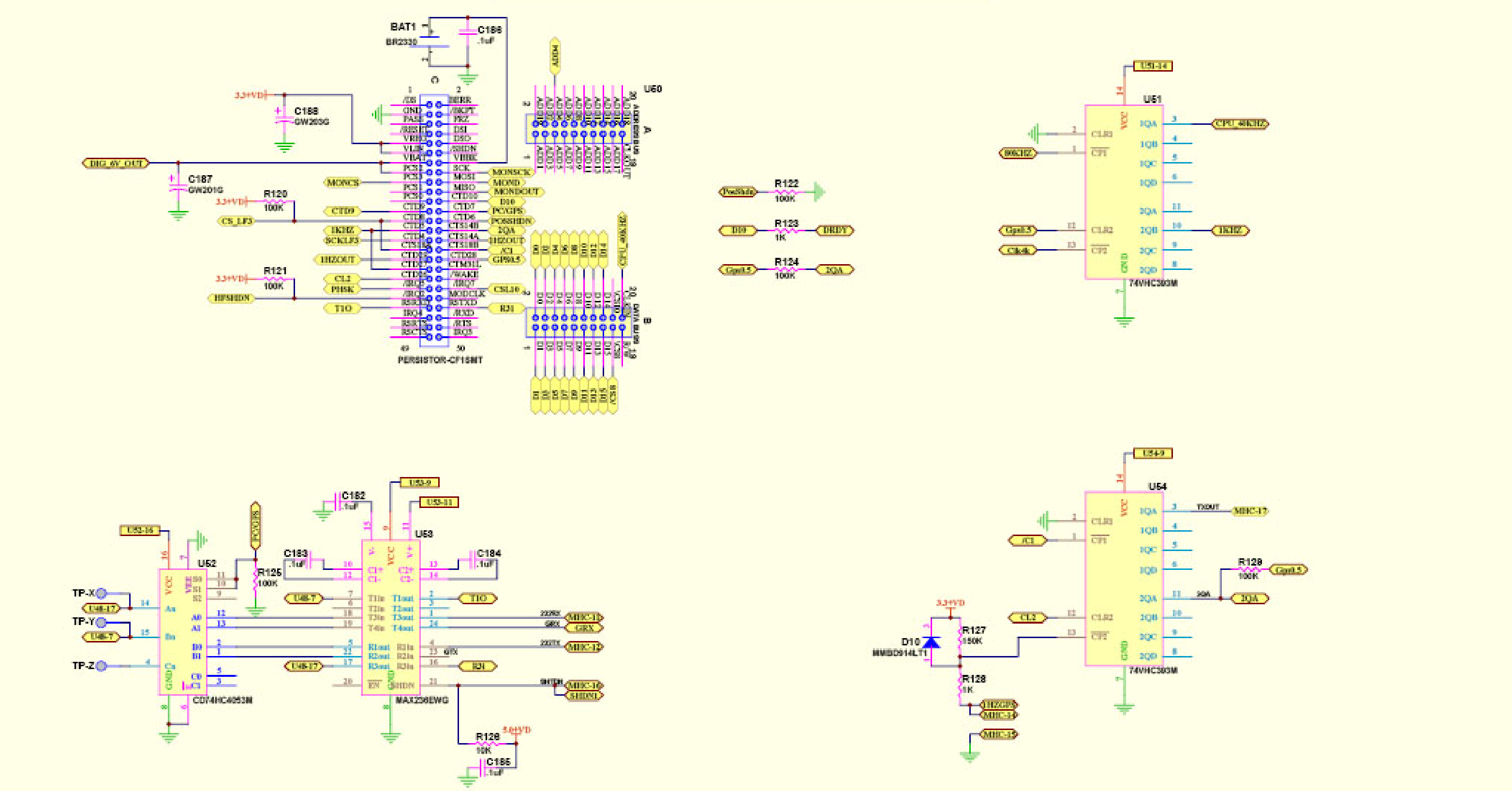
C119A,C,E,G				R82A,C,E,G		
C120A,C,E,G				R85A-H		
C125A-H				R86A-H		
C126A-H				R97-R115		
C127A-H						
C128A-H						
C149-C181						

NOTES:

DIGITAL CPU & RS-232 SECTION



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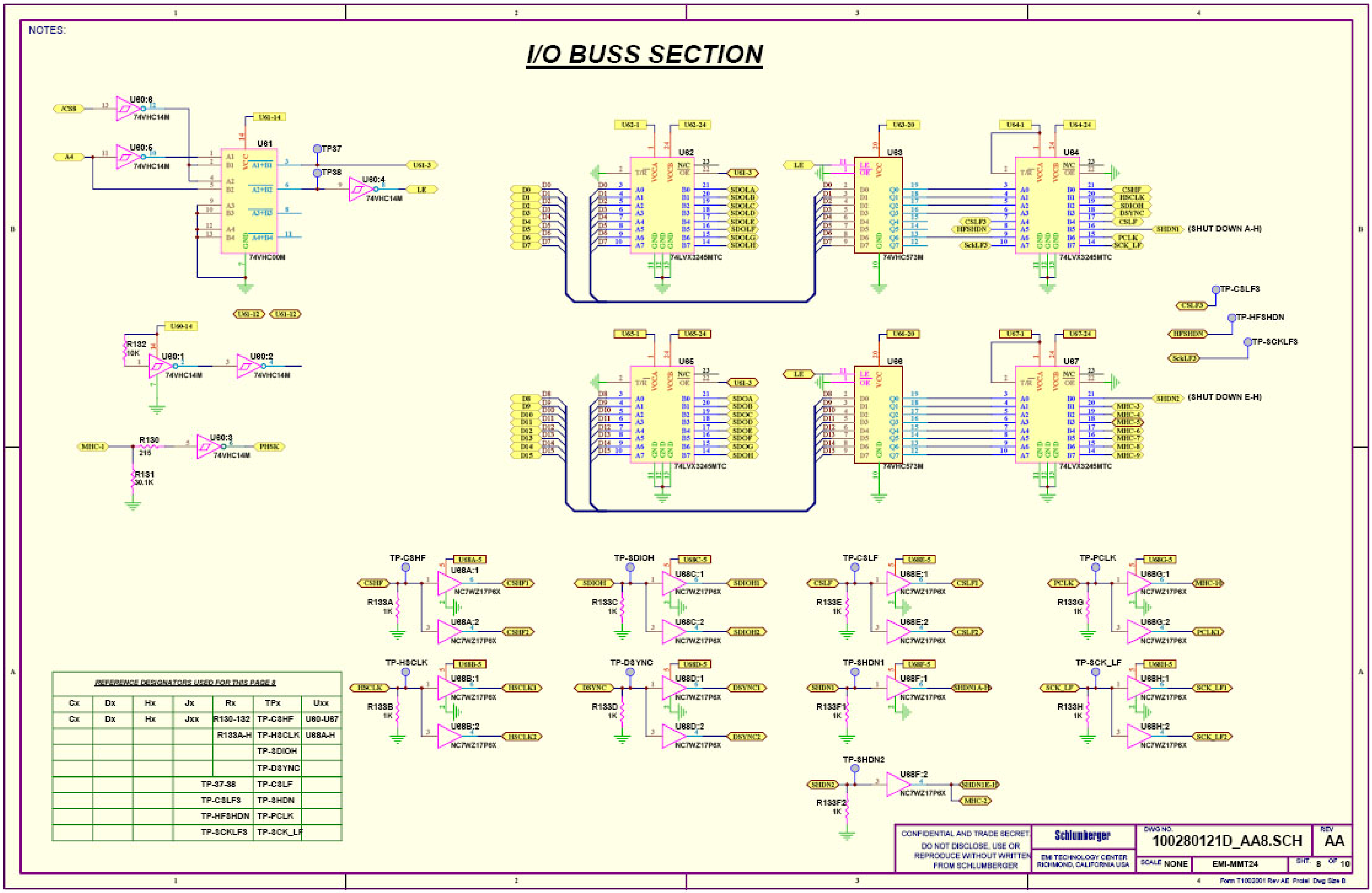

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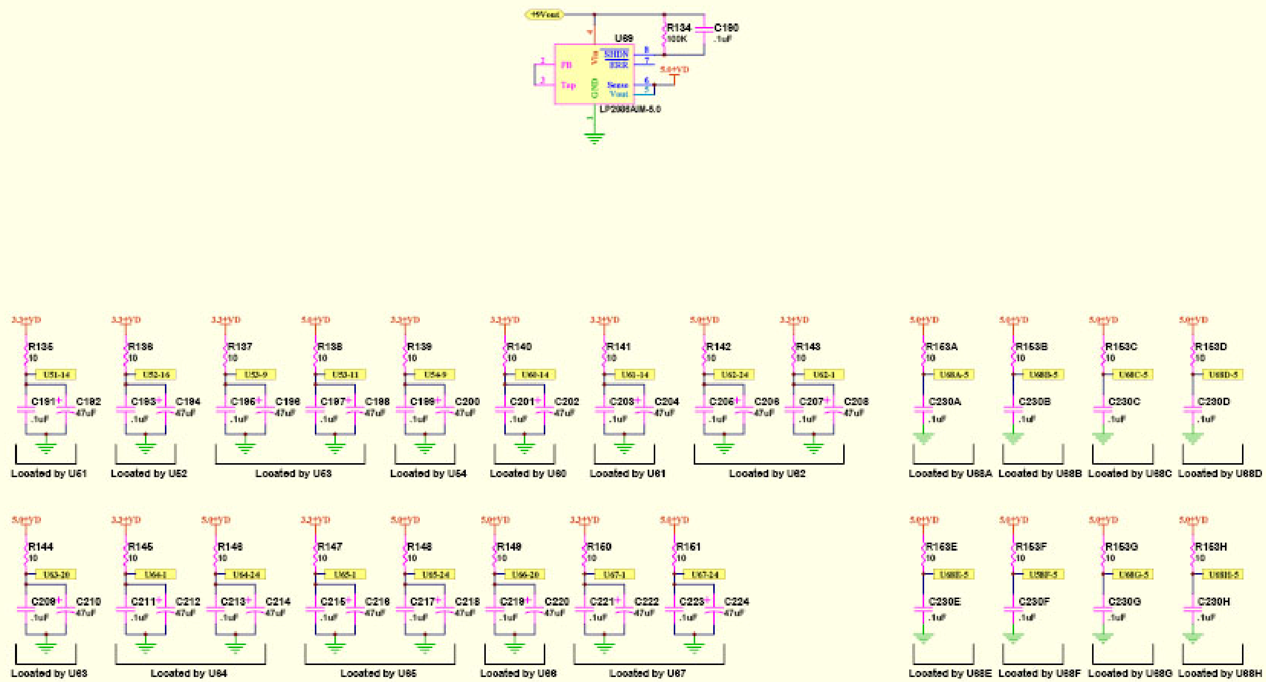
				R133A-H	TP-HSCLK	U68A-H
					TP-SDIOH	
					TP-DSYNC	
				TP-37-38	TP-CSLF	
				TP-CSLF3	TP-SHDN	
				TP-HFSHDN	TP-PCLK	
				TP-SCKLF3	TP-SCK_LF	

NOTES:

CPU & BUSS POWER SUPPLY SECTION



REFERENCE DESIGNATORS USED FOR THIS PAGE 9

Cx	Dx	Hx	Jx	Rx	TPx	Uxx
C190-C224	Dx	Hx	Jx	R134-R151	TPx	U69
C230A-H				R153A-H		

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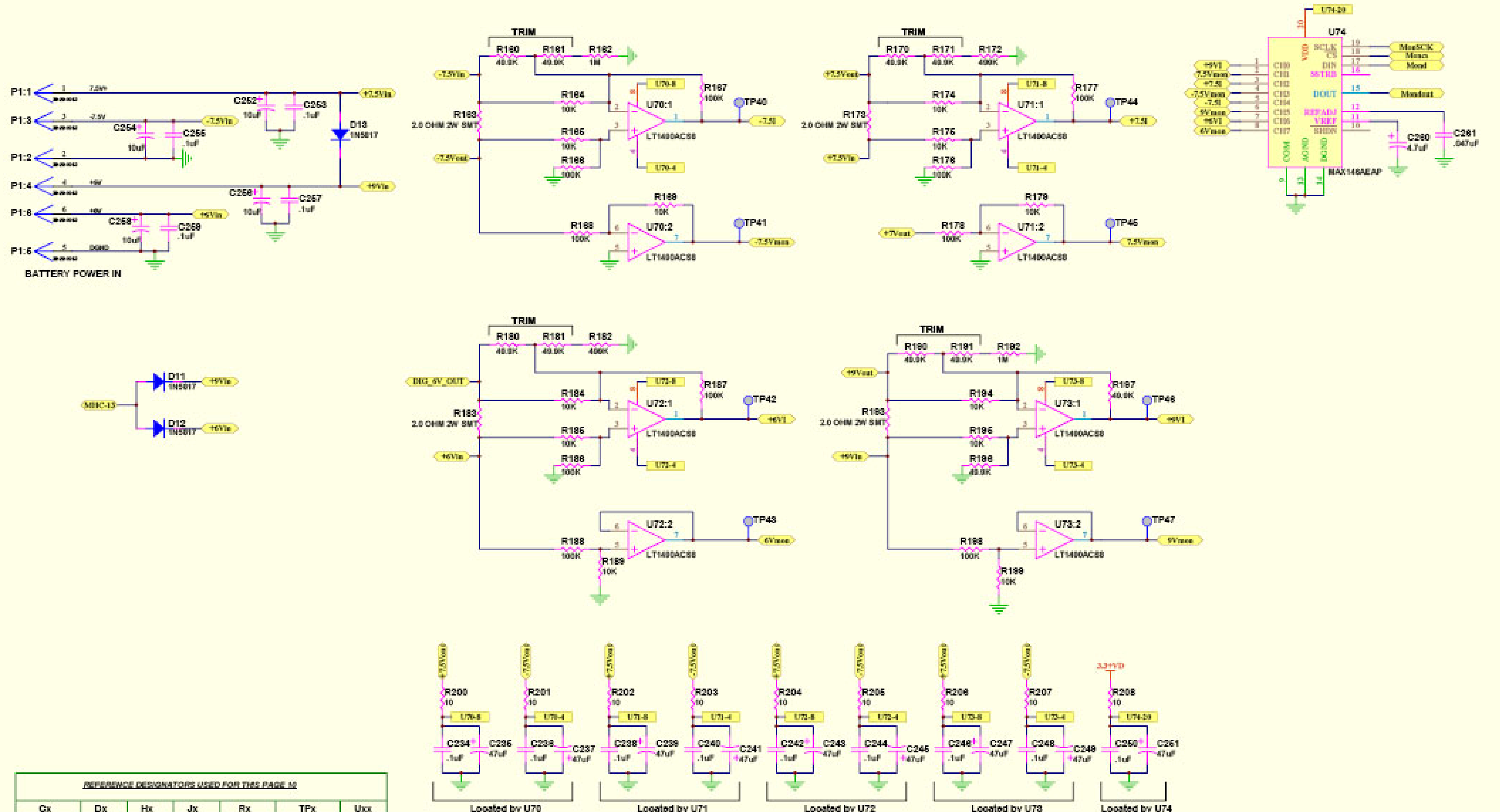
SCALE NONE	EMI-MMT24	SHT. 9 OF 10

Form T1002001 Rev AE Protel Dwg Size B

NOTES:

POWER SUPPLIES MONITOR SECTION



REFERENCE DESIGNATORS USED FOR THIS PAGE 10

Cx	Dx	Hx	Jx	Rx	TPx	Uxx
C234-C261	D11-D13	H2	P1, JP1-4	R160-R208	TP40-TP47	U70-U74

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APPENDIX F: Detailed Explanation of the MT Method

1 Basic Physics of Service/Measurement

This section contains a basic level review of the physical principles of the measurement or techniques used in the service or equipment.

1.1 The Magnetotelluric Method

Magnetotellurics is a low frequency electromagnetic induction method for determining the subsurface distribution of electrical resistivity using measurements of naturally occurring magnetic and electric fields on the surface of the earth. There are two sources for the natural fields used in MT (Figure 6.1). One is in the complex interaction of the earth's ionosphere and magnetosphere with the plasma stream ejected from the sun (the solar wind). The other is the electromagnetic wave that propagates in the earth-ionosphere cavity from lightning discharges.

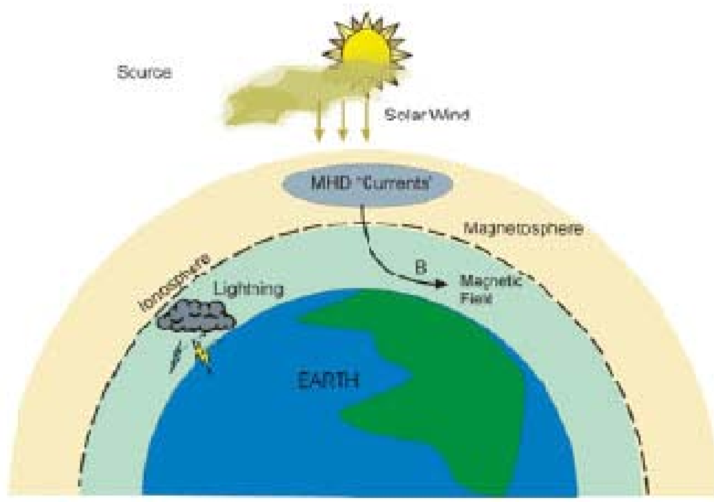


Figure 6.1: Sources for the Natural Fields Used in MT (Schlumberger)

The two sources above provide a rich spectrum of natural electromagnetic fields as shown in the typical power spectrum of Figure 6.2. Below 1.0 Hz, the fields originate in the magnetosphere; above 1.0 Hz, they are due to lightning. The spectra are highly variable reflecting the random intensity of the solar wind. In the past, only very long period magnetic fields were recorded in marine surveys which had penetration depths much greater than the depths of exploration interest.

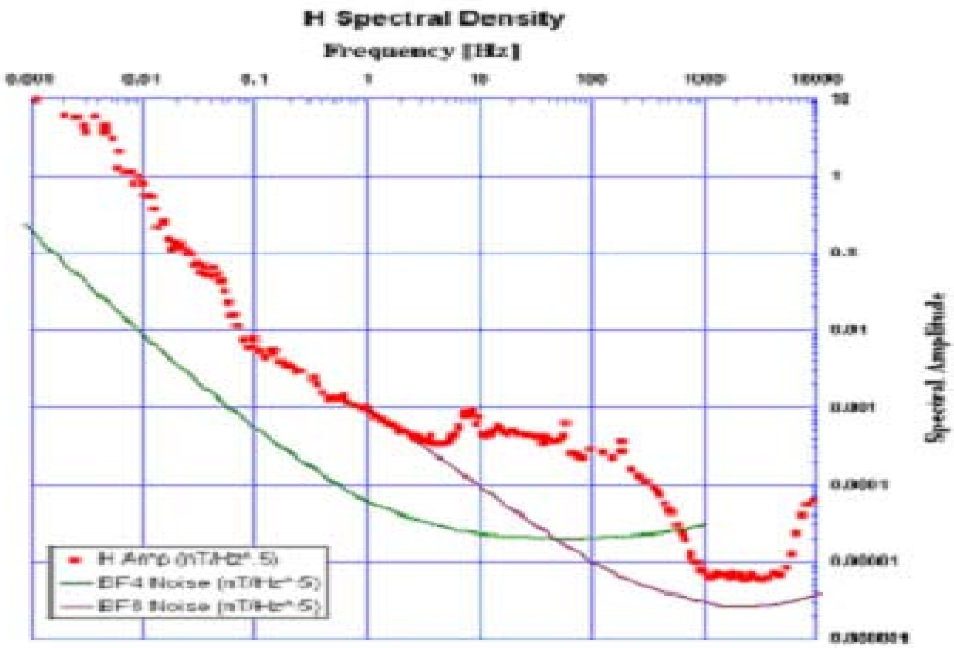


Figure 6.2: Typical Natural Field Power Spectrum. (Schlumberger)

Qualitatively, it may be said that the changing magnetic fields (H) from these natural sources induce an electromagnetic field (emf) in the ground through Faraday's law, which in turn drives currents in the Earth (the so-called telluric currents). The voltage drop (ΔV) between two electrodes implanted in the ground a distance L apart (called an electric dipole) provides the surface electric field,

Equation 6.1

E, via $E = \Delta V / L$

It is observed that the magnetic fields are essentially constant over horizontal scales of hundreds of km and can be considered as plane waves. A simple analysis of the reflection physics involved shows that the ratio of the measured magnetic field to the orthogonal electric field at the surface of a uniform half-space of resistivity ρ is given by:

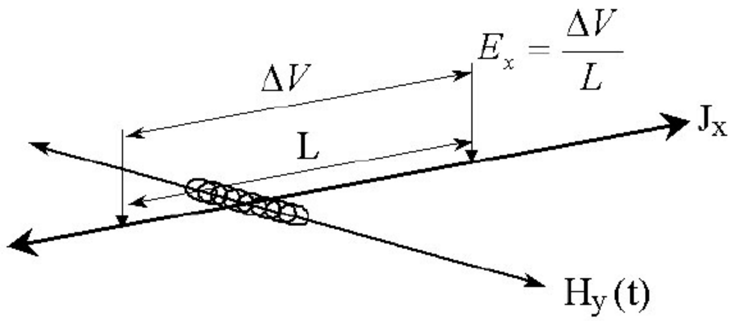
Equation 6.2

$$\frac{E}{H} = \sqrt{i\omega\mu\rho} = Z, \textit{the surface impedance}$$

From the impedance an equation for the apparent ground resistivity can be found:

Equation 6.3

$$\rho_A = \frac{1}{\omega\mu}\left|\frac{E}{H}\right|^2$$

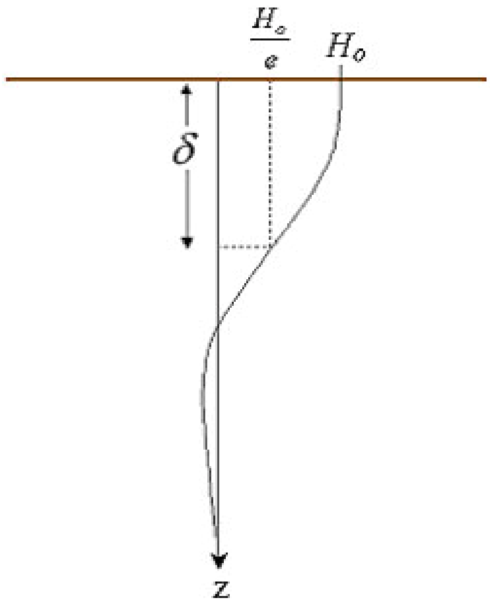


1.2 Skin Depth and Layered Models

Plane wave fields at the surface diffuse into the ground attenuating exponentially with depth. Low frequencies penetrate more deeply than high frequencies, the so-called skin depth effect. The skin depth, δ, is the depth in the ground at which a plane wave is attenuated to 1/e of its value at the surface, given by Equation 6.4.

Equation 6.4

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{2\rho}{2\pi f \, 4\pi \cdot 10^{-7}}} \approx 500\sqrt{\frac{\rho}{f}}$$



In a layered half-space, the resistivity obtained using Equation 6.3, ϱA, is roughly equal to the average resistivity of layers down to the skin depth. For example, for the three-layer model shown in Figure 6.3, high frequencies yield the correct value for the layer as long as the relevant skin depth is within the layer. At lower frequencies the skin depth includes more and more of the second, less resistive layer and the calculated (or apparent) resistivity falls. At very low frequencies, the surface layers are a small component in the averaged section and the apparent resistivity becomes the correct value for the intrinsic resistivity of the basement.

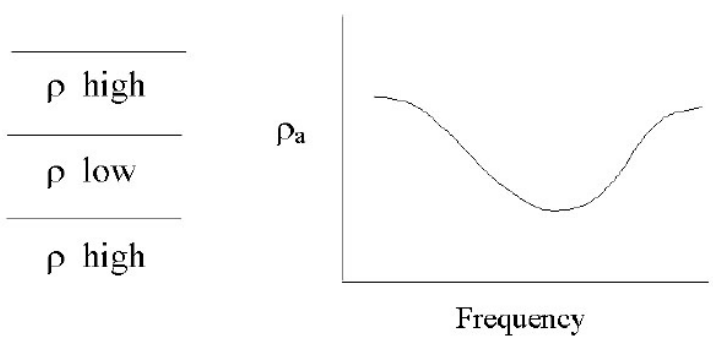


Figure 6.3: Three-Layer Model

The apparent resistivity vs. frequency data is called a MT sounding. At the most fundamental level, interpretation of MT consists in finding the conductivity distribution vs. depth that matches the observed data. Typical exploration surveys record the natural field spectrum from 10-4 to 103 Hz yielding depths of investigation from a few tens of meters to a few tens of km in typical geologic sections.

1.3 Field Spectra and Local Noise Removal

The principal problems associated with the measurements themselves have been the very low amplitude of the fields during periods of low solar activity and the impact of local electromagnetic noise (electric trains, power lines, electric machinery etc.). The former problem has been solved with the introduction of a new generation of magnetic field sensors and the latter with the development of a data processing method using reference fields from a remote site.

Schlumberger has developed a series of low-noise induction sensors, which are recognized as the industry standard for measurement of natural magnetic fields. The noise spectra of two sensors, BF-6 and BF-4 (the sensor commonly used in the MT 24-Bit Low Frequency system), are shown with the natural field spectrum in Figure 6.2.

Remote reference processing makes use of the fact that the incident fields are coherent over horizontal separations of hundreds of km while local noise fields are not. Impedance calculations then use cross-spectral techniques which yield estimates of E and H which are unbiased by the local noise fields. Most field surveys are now done with remote reference processing.

1.4 Impedance Tensors and Spatial Aliasing

Real geologic sections are not uniformly layered and lateral variations in resistively from geological structure and inhomogeneous litho logy cause distortions in the horizontal flow paths of the telluric currents. In general, the impedance is a tensor relating the horizontal orthogonal components of E and H via:

Equation 6.5[16]

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{vmatrix} \cdot \begin{vmatrix} H_x \\ H_y \end{vmatrix}$$

At any point on the surface of the earth, the impedance tensor is an invariant. A complete description of the subsurface resistivity distribution would require that the impedance be measured continuously over the surface – a logistic and economic impossibility. As a practical approach, measuring sites are chosen at separations designed to sample adequately the variation in the fields associated with the resistivity variations from the target depth.

Unfortunately, this approach is not satisfactory if the near surface is highly inhomogeneous. The near surface current flow is continuous everywhere and so the resulting electric field is discontinuous. The measured electric at a site can be biased either up or down from the desired value which reflects the deeper structure. More accurately, the surface data from separated sites can be spatially aliased. In MTs, this effect is known as static offset and it is the most fundamental problem encountered in interpreting MT data

A practical solution introduced by Francis Bostick and Carlos Torres-Verdin[17] is to sample the electric field continuously with contiguous bipoles along a profile roughly perpendicular to geologic strike. This continuous profiling ensures adequate spatial sampling and the near surface effects can then be filtered out. Many commercial land surveys are now conducted in this manner.

1.5 Modeling and Interpretation

The interpretation of tensor impedance data requires the use of full three-dimensional models of the ground. The increase in computing power has been matched with a new generation of inversion codes – the programs that find the conductivity distribution which best fit the data. In the absence of a priori information, inversion yields a necessarily smooth interpretation because the diffusion fields cannot inherently resolve features much smaller than 0.1 skin depth. Subsurface images using these general inverses tend to look fuzzy although general structure is clearly revealed, as is the layering.

A much more satisfying approach (for example, by Smith et al[18] at UC Berkeley and LBNL) has been to incorporate as much information as possible for a hypothetical model before the inversion and then to invert for the parameters (dimensions, thicknesses, lateral extent, resistivities, etc.) of the model. This has proven very effective in mapping base of salt, base of volcanics and depth to basement beneath volcanics. It is also ideally suited to mapping the location of sand/shale sections in carbonate thrust sequences. For this a priori modeling approach, one can use gravity data and preliminary seismic data either to simply guide the initial choice of model or implicitly in the inversion process. These inversion processes have practical resolution of about 5% of the depth

Attachments

As discussed in the body of the report, there are 70 MMT stations recording high-quality MT signals. These MT signals are stored in a standard SEG format--EDI format (more details can be found at http://www.geophysics.dias.ie/mtnet/docs/ediformat.txt). Each station has a data file associated with it. The data in EDI format can be further processed with software packages such as LMMT_XP.

For each profile, there are both amplitude and phase curves. The black is the observed data, and the red is the predicted data. For profiles 1, 2, and 3 only the TE mode data has been used. For profile 4 there are both TE and TM mode data.

These data are stored on a CD accompanying this report.